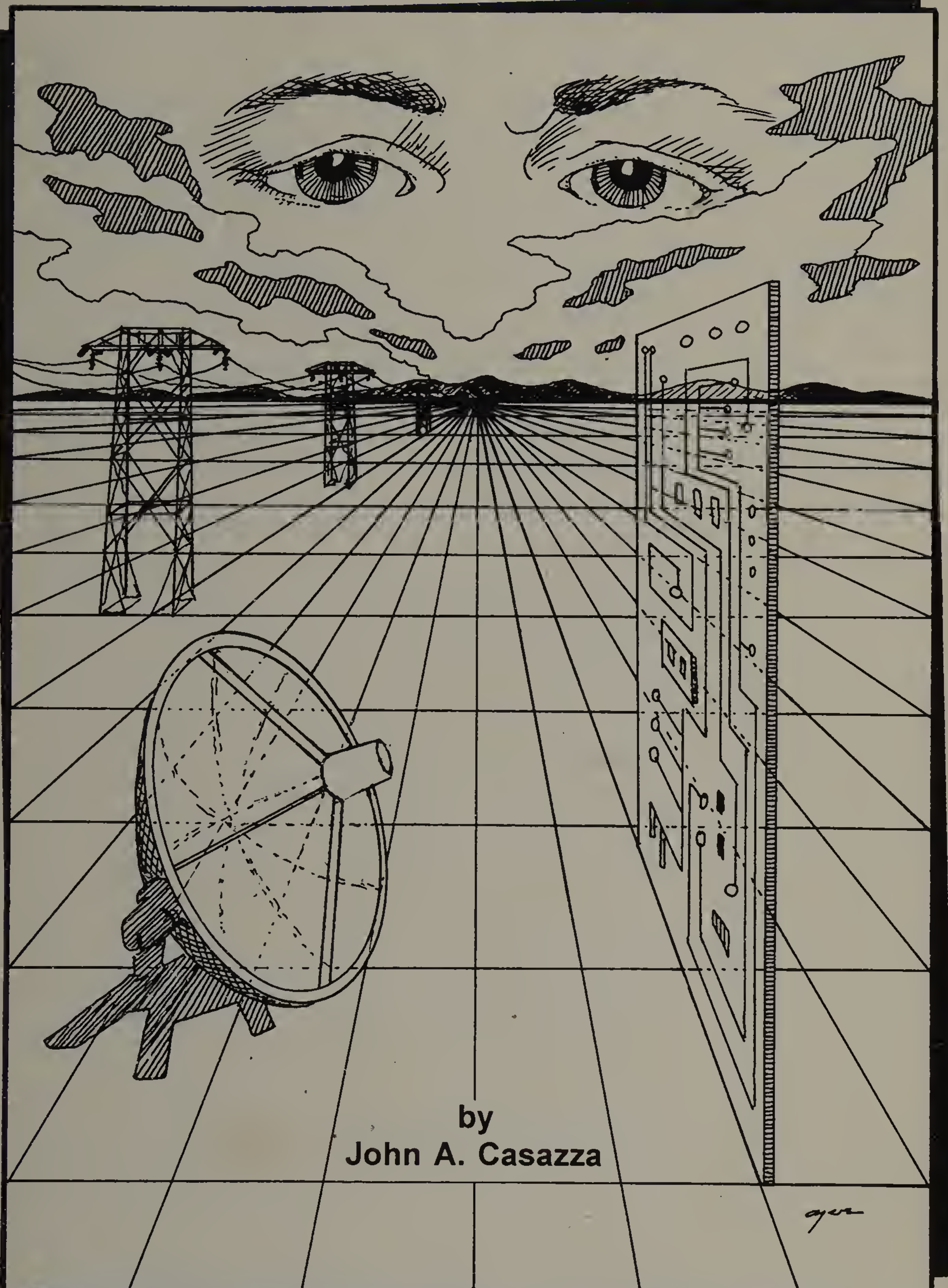
THE DEVELOPMENT OF ELECTRIC POWER TRANSMISSION



by
John A. Casazza

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THE DEVELOPMENT OF ELECTRIC POWER TRANSMISSION

The Role Played by Technology, Institutions, and People

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INTRODUCTION

The "IEEE Case Histories of Achievement in Science and Technology" series takes a close look at major developments and applications of particular fields in electrotechnology and presents first-hand accounts of significant contributions.

Developed to provide practicing engineers with enrichment and interesting insights into important technological advances in their specific fields, this series can also serve to inspire future engineers by expanding the significance of technical knowledge and explaining it within a "real world' business context. Readers are shown the inside picture of the problem-solving process . . . exactly how decisions were made, what factors may have influenced a particular technological development process, and how social, political, and economic conditions at the time impacted what was done.

Authors for this series were chosen based on their unique contributions to advancing technological and engineering practice. Recognized by their peers for their hard work, dedication and devotion to their chosen fields, these individuals, through their close personal association with the process, have cultivated distinct views and personal opinions. Others may see the same events, problems, opportunities or solutions in a different light, but all can appreciate the views of the author.

John A. Casazza, recipient of the prestigious IEEE Herman Halperin Award, is such an individual His contributions to electric power transmission system development and use over the last 40 years have been extensive.

Mr. Casazza has been instrumental in the planning and development of the addition of 500 kV systems used to integrate minemouth and nuclear generation in the mid-Atlantic states and to provide 500 kV ties to other regions; the development of new concepts for improving the utilization of transmission systems through reliance on the short-term thermal capabilities of transmission facilities; the development of the original NERC definitions for network transfer capabilities (these are accepted nationally); the development of an index of transmission system utilization and methods for on-line determination of transmission use by the various electric power systems for the Electric Power Research Institute; his development of and patent for a solid-state device to control the loading on individual ac transmission circuits to allow better utilization of transmission networks; pioneering the applications of the use of high voltage, high capacity phase-angle regulators to increase the utilization of existing transmission facilities and defer the need to construct additional transmission lines; the introduction of the first use of dispatch computers by U.S. utilities to perform transmission system contingency analyses and to evaluate possible corrective actions; and the development of programs to reduce the likelihood of future blackouts.

A Fellow of the IEEE since 1975, Mr. Casazza has taught at the university level, has been responsible for consulting projects in the U.S. and abroad, and has testified extensively before federal and state regulatory, legislative, and judicial bodies concerning electric power issues. He is the author of over 35 articles and publications on a broad scope of energy topics. The Appendix presents additional information on his career.

Mr. Casazza's insights and opinions of the power industry over the last 40 years should be of great interest to those working in power engineering today, those anticipating a career in this field, and those concerned with public policy. His unique point of view on the state of the utilities industry, both in the government and private sector, is based on years of experience. It is a perspective shared by many, but does not necessarily reflect the position of the IEEE.

The Educational Activities Department is committed to providing continuing education materials to the working engineer. Through publications such as the "Case Histories of Achievement in Science and Technology," and with the cooperation of authors such as John Casazza, we are able to encourage lifelong learning for the engineering community.

FOREWORD

We live in a world increasingly affected by rapid technological change. All facets of life and all strata of society are influenced by advances in scientific development. Therefore, when approaching society's problems in search of reasonable solutions, one must consider both the technical and institutional aspects. This book will demonstrate how important it is to seek resolutions that are both technically correct and institutionally sound.

Unfortunately, the U.S. has initiated many institutional changes that are technically flawed due to the lack of technical competence of many of our appointed officials and elected representatives. In some measure, this is also the failure of engineering as a profession. If this book helps engineers to meet their obligations to society, it will have been worth the effort.

This book will present a history of the development of electric power transmission systems in the United States as I saw it and participated in it. The material will interweave technical and societal needs, the progression of the concepts to fulfill them, the people involved and the roles they played. The development of innovative concepts from the idea stage through final useful application will be covered and the roles of various individuals, company officials, government officials, professional societies, research institutes, and trade associations who affected my life will be discussed. A few key individuals and their roles are identified inside boxes in the text. I have put particular emphasis on the basic philosophy that underlies my work.

The objective of this book is to provide some insight into how things are accomplished in our society, the many obstacles to overcome -- whether technical, financial, or economic -- and the interpersonal relationships which are involved. By describing my unique experiences with the press, government officials, and boards of directors, I hope to describe the leadership role engineers need to play. I will also try to point out how often an event that seemed to be a failure turned out, in the long run, to be a success.

Jack Casazza

ACKNOWLEDGEMENTS

While many individuals contributed to my professional career and to whatever professional accomplishments I might have achieved -- and I do not in any way wish to downgrade their contributions -- the contribution of my wife, Madeline, far outweighs all of them. While she was not involved in my technical work, she has totally supported me in raising our family and in guiding our family life. She made many, many sacrifices, where my objectives were met at the expense of things she would have loved and enjoyed. Without her, my career could not have unfolded as it did. She was, and is, the ultimate team player.

In our culture today, many talk about the rights of the individual, women's rights, minority group rights, etc. Madeline never thought in those terms. She always thought of what was best for the family. This willingness to sacrifice one's own aims and objectives for the benefit of the group and for others is sadly lacking in much of our society. A return to these basic values and beliefs is badly needed.

I also wish to acknowledge the contribution of Gregory Vassell who carefully reviewed the draft text and made many suggestions for its improvements which have been incorporated.

Jack Casazza

NOTE: All fees and royalties from this book have been donated to the Cooper Union in New York to further the role played by engineers in setting national policy for electric power.

Chapter 1
THE EVOLUTION OF ELECTRIC POWER TRANSMISSION SYSTEMS IN THE U.S.

> *Three horsepower is the average amount of mechanical power back of the industrial worker in the United States. Less than half as much is available to the worker in other countries. Since a nation's utilization of power is, in effect, an index to its wage scale and its standard of living, it is highly important that we continue to develop our power resources to the utmost.*

This statement from a 1925 study of the future of U.S. transmission systems [1] set the tone for 65 years of expansion. There are many aspects of the early development of these U.S. transmission systems which are relevant to the state of development of power systems in much of the world today. The motivating force for all the actions taken by the utilities and government was the provision of the needed electric supply at the lowest possible cost. The evolution of electric power systems both in the U.S.A. and worldwide has been driven by the twin goals of improved economics and reliability.

The Engineering Philosophy Behind the Development of our Electric Power Systems

The Overall Public Benefit Concept

When making an engineering, business or economic decision, a clear-cut approach is needed. The approach behind the development of the coordinated, vertically integrated and economically optimized electric transmission system existing in the United States today was to consider the overall effect on the consuming public. This included large industrial firms, residential customers, shopping centers, and commercial institutions. The decisions made were, to the best of everyone's ability, in the best interests of the society which the system supplied.

Several key questions needed to be asked about the costs and benefits of this systems development:

- Are we concerned about costs and benefits to the people who create the utility systems?
- Are we concerned about costs and benefits to those who invest their money in them?
- Are we concerned about costs and benefits of the consumers?
- Are we concerned about what is good for one company or another company?

Robert Hooke - The Engineering Philosopher

Robert G. Hooke was Head of the Planning Department at Public Service Electric & Gas Company when I was assigned there. He was an engineer who had obtained a liberal arts degree at Harvard before moving into engineering. Bob had a clear view concerning the role of engineers in our society. He strongly advocated that, in performing our duties, we should do "what is best for the community." He espoused this view for over 30 years in his career and lead me to see and support the overall public benefit approach. He also believed strongly that engineers should contribute more to society than they take from it. I can clearly remember one day, when presented with a plan for a new substation and a new transmission line, he looked out of his window, pointed to the slums of Newark, and he asked, "Well, I see the economic figures but what is best for those people out there?" Bob's approach remained with most of us who were fortunate to work with him.

Many people were involved in answering these questions and in weighing the emphasis and determining the development approach. Robert Hooke was one whose philosophy and carefully thought out approach was influential in the final decision.

We also recognized that if economic decisions are based on a total societal view, the resulting benefits must be shared equitably. They must be shared with those whose creative energy and talent makes them possible. They must be shared with those whose financial resources and funds made possible the execution of the technical and institutional developments. They must be shared with the consumers who are supplied by these systems. This requires that government regulatory officials believe in the overall "public benefit" concept. Sadly, this is not always the case. Administration of the regulatory process has become so cumbersome that many seek alternative methods to resolve disputes [2]. As stated by Donald L. Rushford, former assistant to FERC Commissioner,Charles Ross , [3] "...the formal, adversarial hearing process is the least effective and most expensive way to communicate ever devised by man...the greatest problem facing regulators is a lack of knowledge."

Where the development of plans based on the public benefit concept leads to cooperation and coordination between individual systems, such cooperation requires an equitable sharing of the economic benefits. From time to time, because it cost less, it was better to install a transmission line in one system even though the need for the transmission service was in another system. Similarly, with generation additions, the addition was made at the optimum location even if the need was in another system. This required equitable ownership, cost sharing, and other arrangements to be developed so that the overall public interest could be met.

As stated by Thomas P. Hughes of the University of Pennsylvania in the September 1986 issue of *CIGRE Electra* [4]:

> *Modern systems are of many kinds. There are social systems, institutional systems, technical systems, and systems that combine components from these plus many more...An example of such a technological system, one well known to this audience, is an electric power system consisting not only of power plants, transmission lines, and various loads, but also utility corporations, government agencies, and other institutions...problems cannot be neatly categorized as financial, technical, or managerial; instead they constitute a seamless web...engineering or technical improvements also require financial assistance to fund these improvement(s) and managerial competence to implement them.*

The overall public benefit concept therefore required the cooperation of a great many different segments of our society. The basic optimization approach, which became clear about 35 years ago, was the need to optimize in three dimensions:

- **Geography** - the development of a transmission system that was best for the entire region affected was the solution that should be selected. Solutions that were best for one company, one town, one locality, one community, and one state that caused penalties in other companies or jurisdictions were not necessarily the optimum. A total regional approach was taken in developing and planning transmission systems.
- **Time** - the planned developments and technologies used in building our alternating current (ac) transmission systems were not chosen based on what was best for this year, five years from now, 20 years, or 40 years from now. The technology selected and the specific plans implemented were based on the desire and objective of installing facilities that would optimally meet the needs of the public over the full spectrum of time during which the utilities would be in existence, typically more than 30 years.
- **Function** - the plans for the transmission systems were selected and the technologies chosen to meet not only the transmission requirements, but also to recognize the effects on the costs of generation plants, the substations, and the distribution systems which they supplied. Choices which appear to have the least cost from a transmission viewpoint but which caused cost penalties in either the development or operations of generation plants or distribution systems were not made if these penalties exceeded the transmission system savings.

Behind the development of the outstanding electric power systems we have in the U.S. was this underlying philosophy which was practiced by the vast majority of my peers in their work over a 40-year period. There are those in our federal and state governments and in our utilities at this time who are advocating changes that would abandon this " 'public benefit' three-dimensional optimization" approach. They fail to recognize the need to coordinate our technical and our institutional solutions.

There are those who, motivated by personal power and to enhance their careers are ready to completely scrap the technical and institutional procedures which have laid the foundation for the greatest, most reliable, most economic electric transmission system on the face of the earth.

Why an Integrated and Coordinated Electric Power System?

The early technical pioneers, such as Edison, Westinghouse, Tesla, Steinmetz, and others were instrumental in developing our modern electric power technology. The specific individuals I will concentrate on are those who contributed to the building of the electric power systems as we now know them.

Key among these worldwide were Charles Stone, Edwin Webster, Charles Merz, Oscar von Miller, and Ernest Mercier [4]. These gentlemen recognized the advantages of diversity that can be achieved through coordination and systems interconnection. During my career I have seen the following beneficial use of diversities made possible by our transmission systems:

- **The diversity between the times at which peak loads occurred on different systems.** Through interconnections, this allowed the same generating equipment, and sometimes the same transmission equipment, to supply more than one load.
- **The diversity of outages.** Recognition that equipment failures occurred at different times and allowed the use of the same spare capacity for multiple purposes, significantly reduced the investment in generation and transmission facilities.
- **The diversity in fuel sources.** There are times when hydro energy is plentiful and there are times when coal costs are cheaper than oil; etc. This has allowed the use of the minimum cost energy resource on a total regional basis through the interconnection of these systems.
- **The diversity in risk, the diversity in uncertainties.** Because individual systems make projections that are sometimes high or low, and which may be conservative or optimistic, the coordin-

ated planning and operation of their systems allowed the total region to take advantage of the diversity in these uncertainties. Where one system depended on oil and another system on coal, unanticipated price changes or changes in the availability of the fuels due to international situations, strikes, floods, etc., could be alleviated through the diversification of risk.

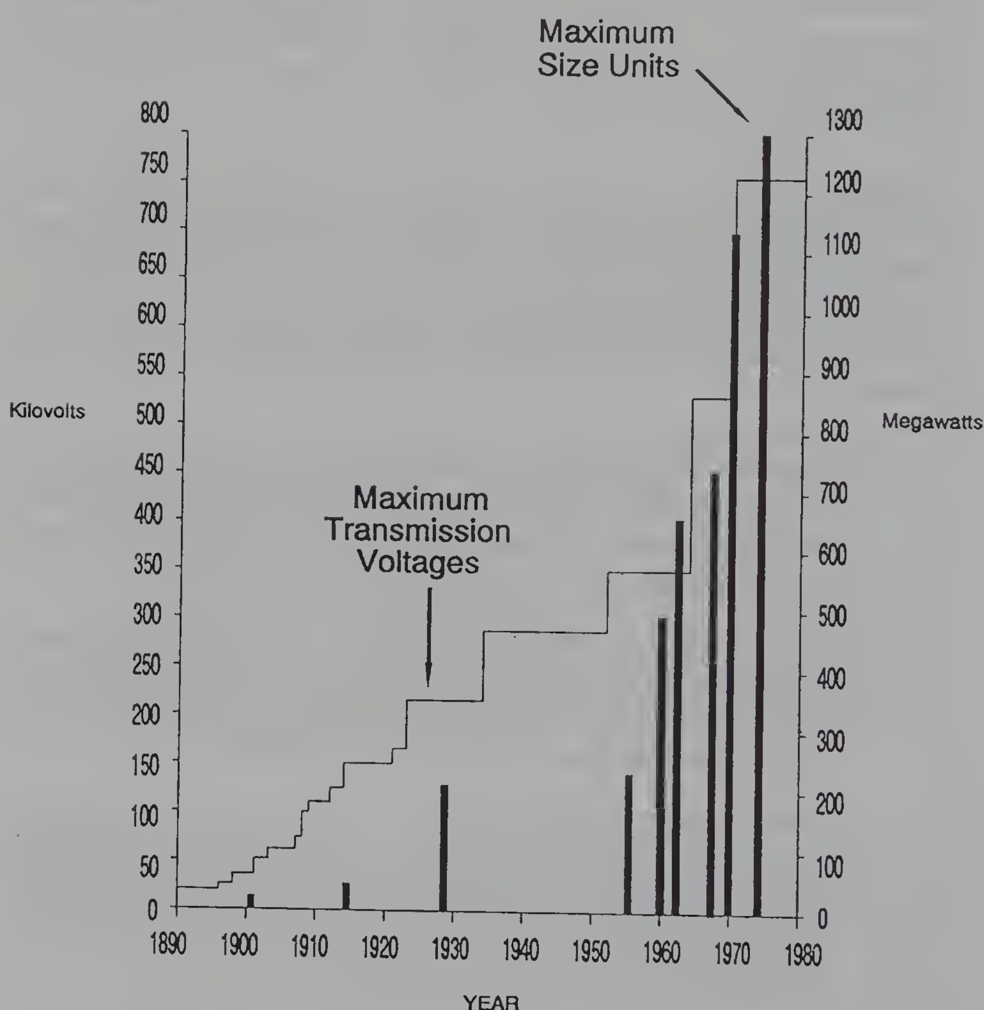


Figure 1. Evolution of Maximum Generation Unit Sizes and Maximum Transmission Voltages

The increasing interconnection of systems and the expansion of the regional grid resulting from the beneficial use of these diversities required the use of higher and higher transmission voltages. The move from 138kV to 230 kV, to 345 kV, to 500 kV, and 765 kV in the U.S. was all part of the developing transmission technology. These voltage increases met the needs of the more economic larger generators being developed, as shown in Figure 1. They also helped the network to deliver power over longer distances with minimal losses.

Stages of Development [5]

The development of transmission systems in the U.S. proceeded through four broad stages of development, as shown in Figure 2, each of which lasted approximately 25 years. As these stages evolved over 100 years, the purpose of the transmission systems also evolved.

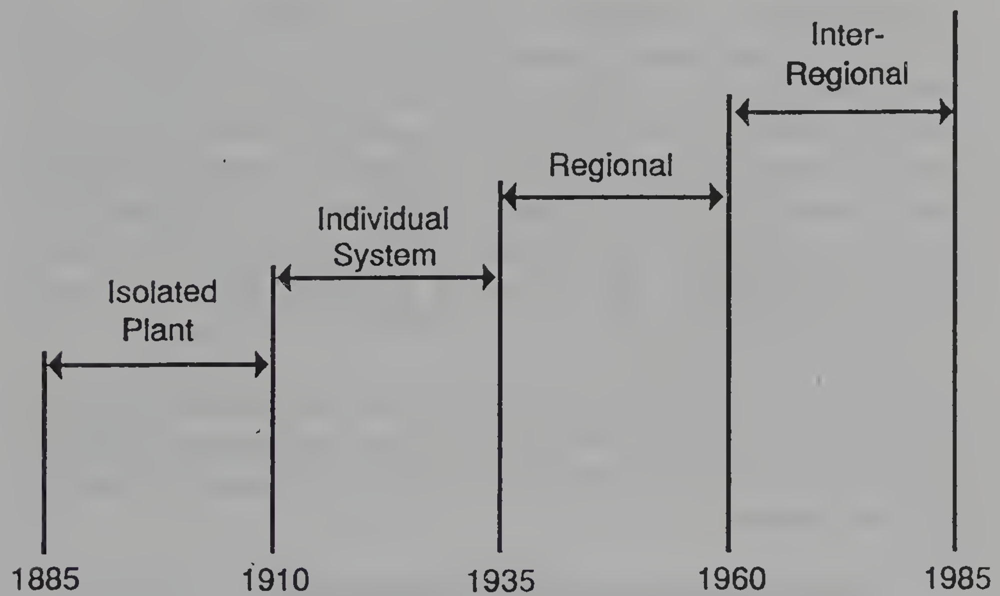


Figure 2. Stages of Transmission Systems Development

Isolated Plant Stage

The first electric utilities served very small areas. These systems typically consisted of an isolated generating plant that was directly connected to a load area. The purpose of transmission in these systems was solely to deliver power. The generating plant had sufficient generating capacity to meet peak electrical needs of the users. Because of equipment failures and the need to remove generator units from service for maintenance purposes, several units were generally installed, providing extra generating capacity. These additional generating "reserves" were necessary at each plant.

Each of these individual plants had separate owners. While consolidation of ownership occurred in the individual system stage, which is discussed next, the separate ownership of individual plants and lines was the seed which produced the pluralistic electric power system structure that exists today. This ownership arrangement differs from that of other countries where it is often believed that electric power transmission system should be a centrally-owned monopoly.

Individual System Stage

These isolated plants and load areas were then connected to each other to form several dozen separate systems supplying major population centers such as New York, Philadelphia, and Chicago. The connections that were installed to establish these systems were economically justified by: 1) the replacement of very small units that were expensive to operate, with larger, more efficient ones; 2) the increased value and use of the available hydro electric capacity; and 3) the sharing of generator reserves among the various plants reducing the total capital investment required. These interconnections also provided improved reliability of service.

At the end of this stage, there were single systems serving the major cities. They had peak loads of 75-500 MW, maximum transmission voltages of 132 kV and units as large as 60 MW. The purpose of transmission at this stage was fourfold:

- Deliver power from generating plants to loads
- Tie the generating plants together to pool reserves
- Allow the production of electricity at all times at the source having the lowest incremental cost
- Make possible the location and use of the lowest cost units available.

Figure 3 shows the transmission systems as they existed in 1919 in the Chicago area.[1] The lines were relatively few and supplied local areas from local power sources. The additions from 1919 through 1925 were merely an extension of this kind of system. By 1925, these systems had not really been linked together and the first intersystem ties were under construction.

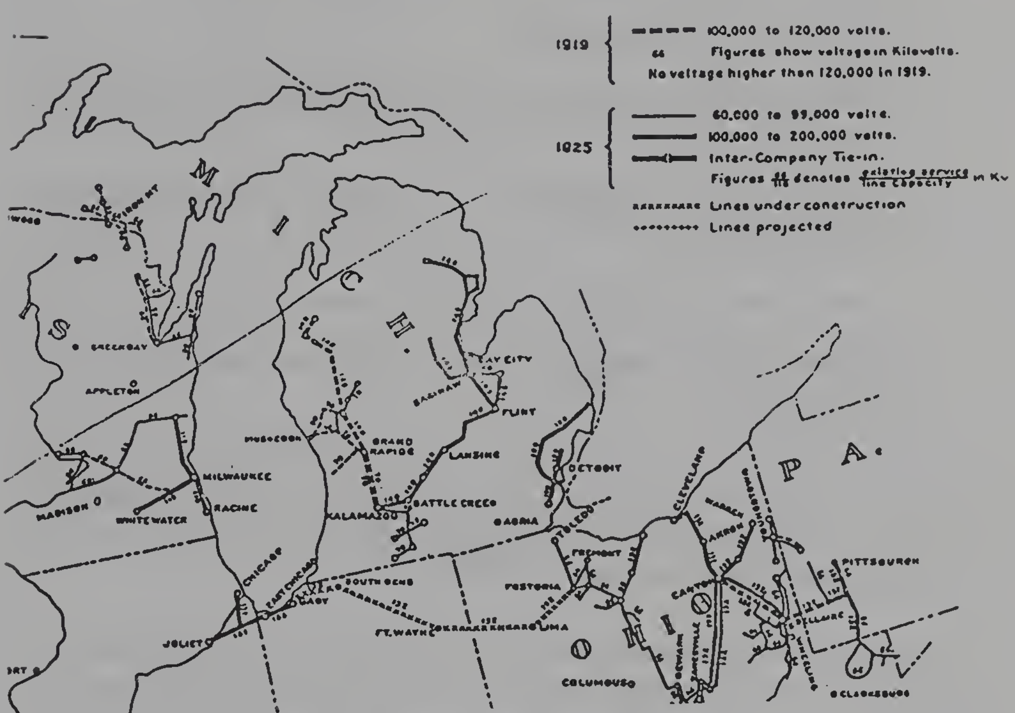


Figure 3. Transmission Lines - Chicago Area 1928

Regional Stage [6][7][8][9]

The process continued as the individual systems were interconnected forming regional systems which operated in synchronism. These interconnections provided savings by:

- further reducing the requirements for installed generation reserves
- taking advantage of seasonal, daily, and hourly load diversities between systems
- scheduling the production of energy at the lowest cost sources available in the region
- reducing operating reserves
- making remote hydro and remote minemouth coal plants available to more users
- using "excess" hydro energy to replace thermal energy in a neighboring system
- using even larger and more efficient generating units
- making possible early use of the best regionally available power plant sites

The use of transmission to reduce generating capacity requirements and fuel use is discussed further in Chapter 3, along with the methods of allocating the resulting economic benefits.

To take advantage of these new interconnections between systems having different owners, it was also necessary for the interconnected systems to develop contractual arrangements for coordinating their planning, design and operation.

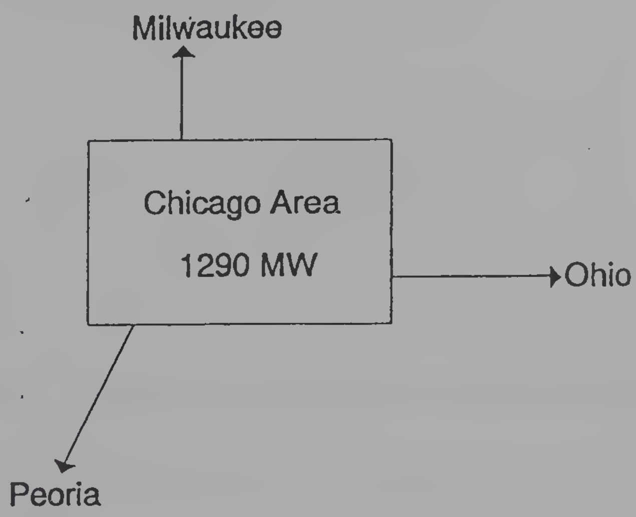
As time went on, the systems continued to grow, and interconnections between the systems began to transfer power and share generating reserves. The operation of these initial interconnection lines was successful and produced major savings. A review of the transmission links built to achieve these interconnections can provide valuable insight into the relationships between transmission capacities required and the key factors involved. These key factors, which are related to the smaller of the systems, are peak load of the system, largest unit in the system, and largest plant in the system.

TABLE 1

TRANSFER CAPABILITY PROVIDED FOR INITIAL INTERCONNECTIONS BETWEEN REGIONS

		Initial	Smaller System Characteristics		
Area	Year	Transfer Capability MW	Capacity MW	Largest Unit MW	Largest Plant MW
Chicago (to 3 neighbors)	1928	125 (9.8%)	1290 (100%)	90 (7%)	315 (24%)
Southern ISG (to Northern ISG)	1938	185 (11%)	1600 (100%)	50 (3.1%)	100 (6.2%)
PJM (to CANUSE)	1962	1000 (6.7%)	15000 (100%)	365 (4.8%)	725 (6.7%)

Note: Figures in parentheses are percentages based on total capacity for smaller system in each area.

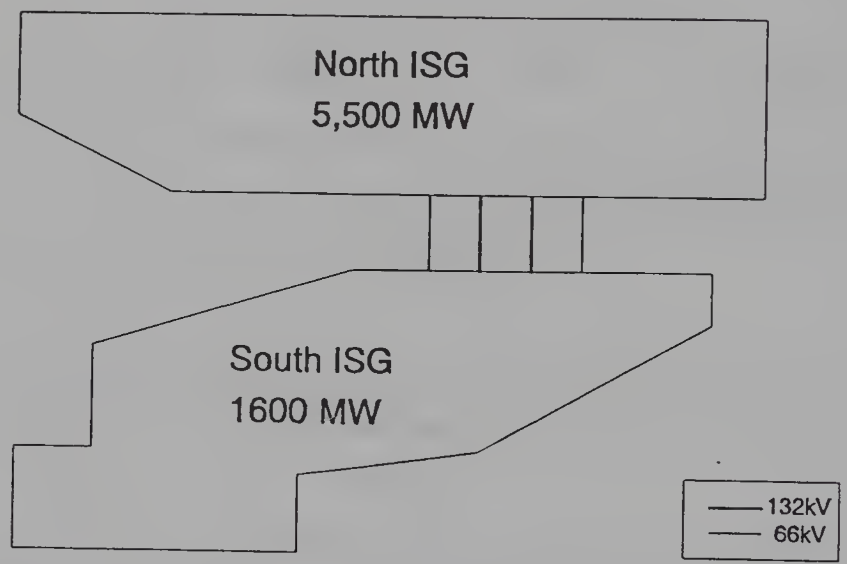


Approximate Transfer Capability - 125 MW, 9.8% of System Capacity

Figure 4. Chicago Interconnection-1928 (all at 132kV)

Figure 4 shows that by 1928, the systems in the Chicago area had three interconnections of 132 kV with their neighbors providing a transfer capability of 125 MW. The other key variables and a number of key ratios are shown in Table 1. The percentages shown in Table 1 are typical for the initial interconnections between isolated systems.

This stage reached a climax in the Midwest in 1938 when the northern and southern portions of the Interconnected Systems Group were interconnected to operate in synchronism as shown in Figure 5. The two groups were, respectively, 5,500 MW and 1600 MW in size. The two 132 kV lines and the two 66 kV lines which were utilized to establish this interconnection provided a transfer capability of about 185 MW. This equals a transfer capability of approximately 11% of the smaller of the two systems involved. The largest unit and plant were 3.1% and 6.2%, respectively.



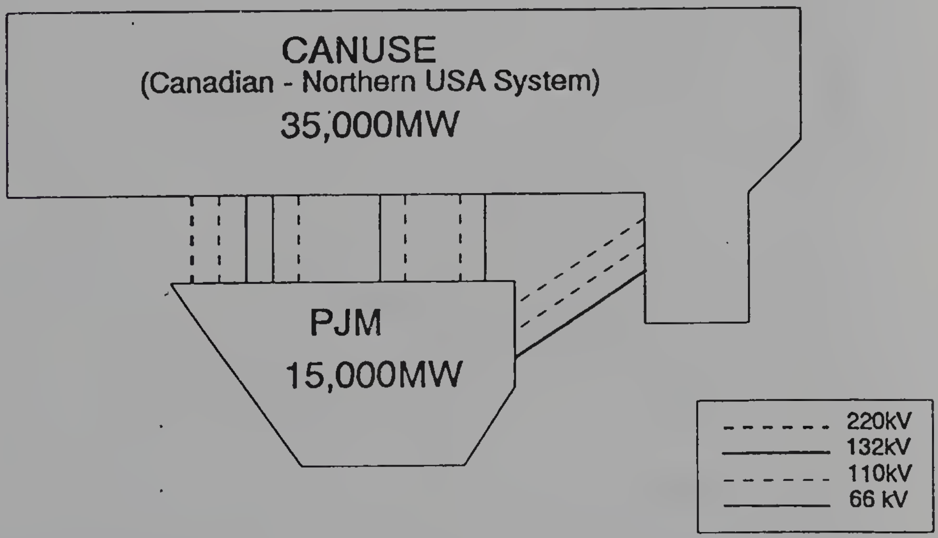
Approximate Transfer Capability - 185 MW, 11% of Southern ISG System

Figure 5. Interconnected System Groups (ISG) - 1938

The regional systems, which were largely in place by 1940, continued to strengthen the interconnections within their regions for the next two decades. This allowed further economies by building still larger and more efficient generating units; developing larger jointly-planned facilities in which a number of systems participated; buying and selling "excess" generating capacity; more optimum use of hydro electric capacity; increased reliability; and large scale economy energy exchanges over long distances. The maintenance of reliability presented some special institutional and technical problems which are discussed in Chapter 3.

Interregional Stage

In 1962, the Pennsylvania-New Jersey-Maryland system (15,000 MW) interconnected with the system to its north, then called the CANUSE system (35,000 MW), by closing 12 tie lines as shown in Figure 6. Of these 12 tie lines, one was 220 kV, one was 138 kV, four were 115 kV, and four were 69 kV. The approximate transfer capability of these interconnections was 1,000 MW or 6.7% of the PJM system capacity. The largest unit was 355 MW (2.4%) and the largest plant was 725 MW (4.8%).



Approximate Transfer Capability - 1000MW, 6.7% of PJM Sytem

Figure 6. PJM Integration with CANUSE - 1962

Figure 7 shows the five synchronous areas that currently exist in North America. All the systems within each area operate in synchronism. Four of these areas are interconnected by direct current (dc) ties. The purpose of the interregional interconnections was to further reduce the generation reserves and production costs by integrating the regions, much in the same way as the individual systems had been integrated 25 years earlier to form regions.

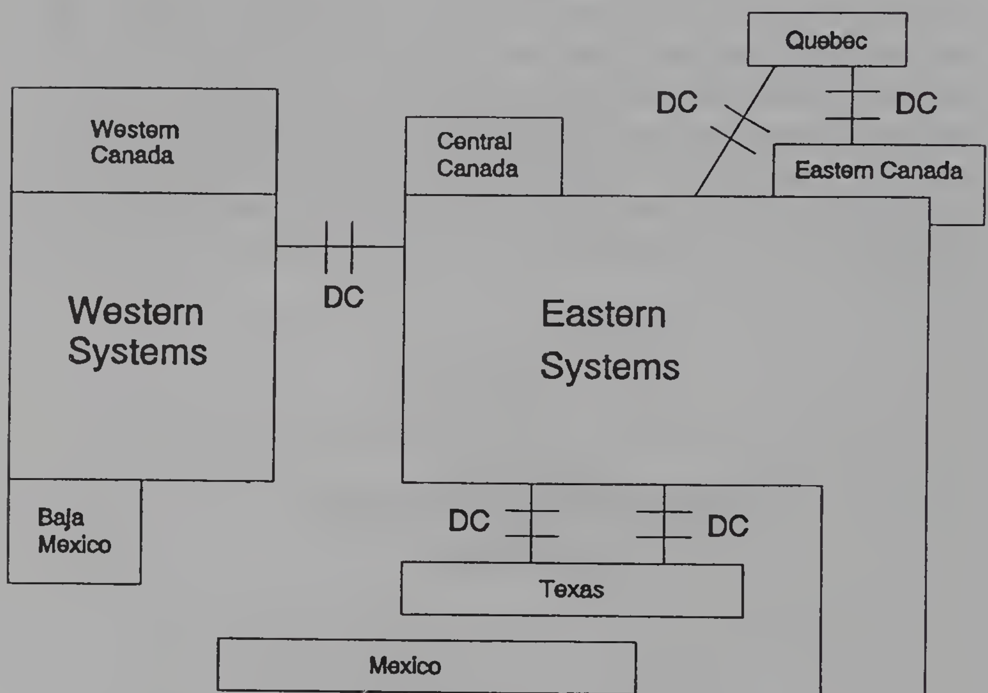


Figure 7. The Five Synchronous Systems of North America

Interconnection Capacity vs. Key Factors

Initial Interconnections

Table 1 provided a review of the 1920-1980 experience in the U.S. disclosing general relationships between the total simultaneous interconnection capability and system size; largest unit; and largest plant. These relationships are a result of engineers doing a multitude of load flow, stability, voltage, and economic studies. A transfer capability of 7-11% of the smaller system capacity has typically been provided for all initial interconnections between areas.

Present Interconnections

Figure 8 shows transfer capabilities of about five times the size of the largest unit or two times the largest plant in the system have been the general rule since 1980. One of the first engineers to recognize some of these key relationships was Charles Concordia, then with the General Electric Company.

Charles Concordia - The Self-Taught Genius

In 1950 I was sent to the General Electric Power Systems Engineering Course in Schenectady to improve my technical background for the system work I was being groomed to do at Public Service. There I met an individual who impressed me greatly -- Charles Concordia. Charles was someone mostly self taught and tended to be less bound by traditional approaches. Yet he is one of the clearest thinkers I have ever met. Charles' ability to analyze and define a problem, look at the key variables, and understand their relationships, was an inborn gift of God. He honed and developed this ability through many years. While at Schenectady, and in many cases later in life, I have found that the ability to discuss a situation or a problem with Charles Concordia would always lead, in a short time, to new insights and new approaches. His ability to view a problem from a different direction than the vast majority of other engineers was the real source of his genius.

Charles Concordia helped me understand the technology of systems, their dynamics, synchronous machinery and many other subjects. But more than that, he taught me to try and take a total system view, a creative approach, and look at problems from different angles. I have often been surprised with the results of an unusual approach to a problem.

In addition, he showed me, and many others, the tremendous value of continuing to learn throughout one's life. The education process should never end.

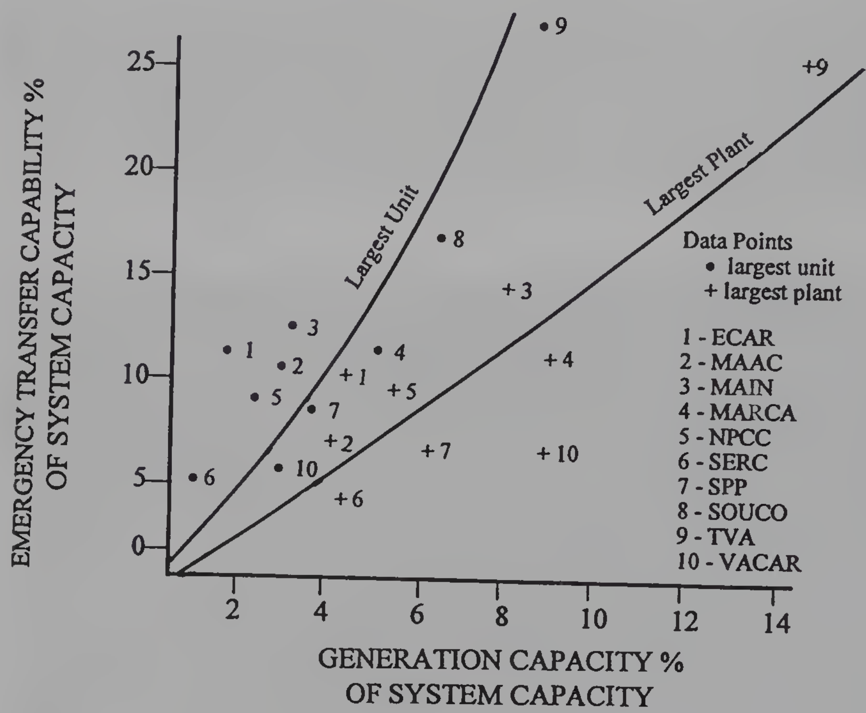


Figure 8. Relationships Between Simultaneous Emergency Transfer Capability and Size of Largest Unit and Largest Plant as a Percentage of System Capacity [5]

These are rules of thumb learned from more than 65 years of experience. Their applicability to other parts of the world is worthy of consideration. The amount of ac transmission capacity required between areas depends on many factors: generator unit sizes; plant sizes; fuel resources; and the normal level of transfers. They show that significant economic benefits can be achieved by providing transfer capabilities of 7% to 11% of the smaller system's generating capacity. Studies are necessary for any particular situation; however, these rules of thumb have proved very valuable in making initial screening evaluations of various plans to interconnect regions in synchronism.

Multi-directional Transfer Paths

As the interregional network has grown in the U.S., and higher and higher transmission voltages have been superimposed, each region developed its own characteristics. One is the number of distinct transfer paths or corridors, into and out of regions. Each transfer path usually consists of a number of circuits of differing voltage, length, and impedance. Analyses of the actual transfer capabilities of specific transfer paths have led to approximations useful in planning the future. One is the "effective capacity" of transmission circuits of various voltages. While the transfer capacity can be limited by a number of different causes, including division of load between circuits, stability, thermal limits, or voltage limits, an unusual consistency observed indicates the effective capacities shown in Table 2. [10]

TABLE 2

TRANSMISSION CIRCUIT EFFECTIVE CAPACITY

Circuit Voltage (kV)	Effective Capacity (MW)
115/138/161	75
230	200
345	400
500	700
765	1500

These numbers are not the actual capacity of the individual circuits. Rather they are, on an average basis, what history has shown to be the effective contribution to the total transfer capability, from circuits of the indicated voltage. In any specific situation, the value of a circuit may be considerably different from the values shown. Table 2 shows the use of average numbers for conceptual planning of transmission networks. This is a very helpful tool. Verification through detailed stability and load flow studies is, of course, necessary after the conceptual network has been proposed.

There is a second effect worthy of note when individual systems are linked together, particularly when they surround a large undeveloped area such as a major mountain range or a very large lake. Because the individual systems have phase angle differences across them, when they are connected in a closed path, the sum of these individual phase angles is usually not zero even when each system is supplying its own load. The net phase angle difference will cause a circulating power flow, which is called "loop flow." This loop flow will be approximately equal to the net phase angle difference divided by the reactance of the path.

As a result of loop flow, and parallel path effects, the simultaneous transfer capability over a number of transfer paths is considerably lower than the sum of the transfer capabilities of the individual transfer paths. In the 1980-1985 period, the overall national average for the ratio of the simultaneous transfer capability of all paths into a region to the sum of the individual transfer capabilities of these paths to a region was about .55, with a range from .40 to .70 for the regions having three or more transfer paths to other regions. The simultaneous transfer capability into the various regions in the U.S. also averaged from 4% to 12% of the regional generation capacity. This shows that the transfer capabilities provided into a region, when expressed as a percentage of the regions' capacity, did not change significantly from the initial values as shown in Table 1.

Use of average data, based on multiple studies and situations as presented above, provides a valuable tool for system planners and designers. It helps to narrow down the alternatives to be studied in detail using modern computational tools.

Technical Developments and Limiting Factors

As the transmission systems in the U.S. developed through the four stages, the superposition of higher and higher voltage transmission became necessary to economically provide the additional transmission capacity required by the larger unit sizes and to limit short circuit duties at the lower voltage busses. The maximum transmission voltages and unit sizes used are shown in Figure 1[11]. The developments in technology required to achieve these increases are discussed in Chapter 3.

As interconnections grew, networks became more complex, increasing the impacts of systems on each other. This presented ever-increasing difficulties in analysis. In the early 1960s a need arose to analyze in detail networks having more than 1,000 nodes or busses. This required the development of improved computational tools.

The factors determining the capability and the development of the transmission systems also evolved. In the isolated plant stage and individual system stage, systems were sparsely developed and their growth was frequently limited by stability and voltage considerations. As these systems evolved into the regional and interregional stage developments, their transfer capability has been determined more and more frequently by thermal limits and acceptable short circuit duties. As inter-regional power exchanges have increased over longer and longer distances, voltage drops have begun to limit power transfers again.

Circulating Power, Loop Flow, and Parallel Path Flow

This increasing size and complexity of the transmission network was not without problems. In the 1960s, system operators began to notice what appeared to be very large circulating power flows around Lake Erie after a complete loop had been established. At times, these circulating power flows reached 1000 MW, either clockwise or counterclockwise.

These flows were the result of the network characteristics and distribution of loads and generation. Similar circulating flows were also experienced on the West Coast around the periphery of the Rocky Mountains. These circulating flows around mountain and lake areas extended over large geographic distances from hundreds to almost a thousand miles.

Some of us involved in these network studies recognize that there were really two independent but superimposed phenomena that determined circulating power flow. The first I called "loop flow." This is the power that flowed completely around any closed transmission path even when each of the interconnected systems was supplying its own loads from its own sources. This is illustrated in Figure 9. The second I call parallel path flow. This is the power that flows over transmission paths in various systems as a part of a power shipment from one system to another. Figure 10 [12] shows that when power is shipped from Ontario Hydro to New York State, some of it flows as far west as Ohio and as far south as Virginia. Figure 11 shows the percentage of power flows through various transmission paths for a power shipment from the Pacific Northwest to Utah [13]. Note that 33% flows through Southern California and 30% through Arizona.

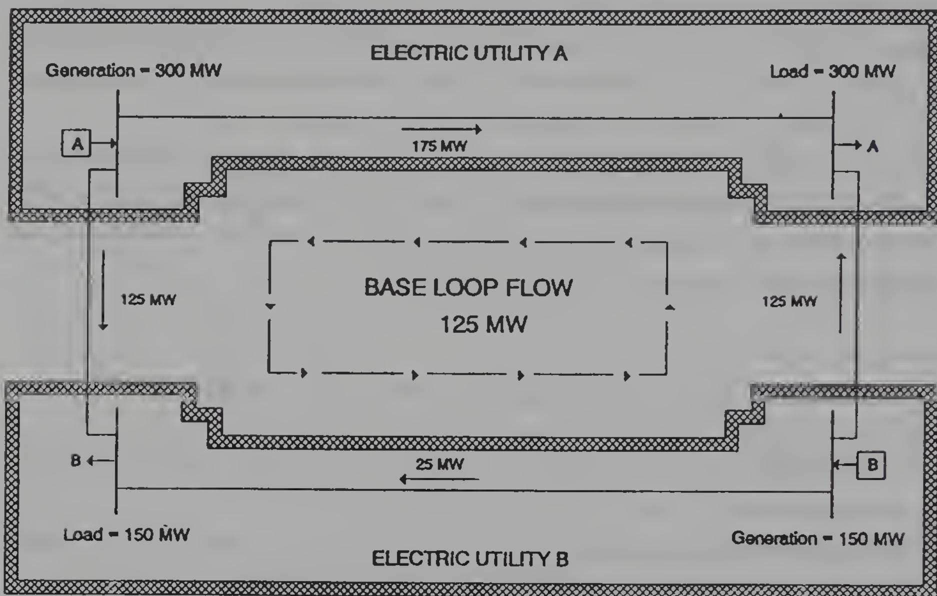


Figure 9. Example of Loop Flow

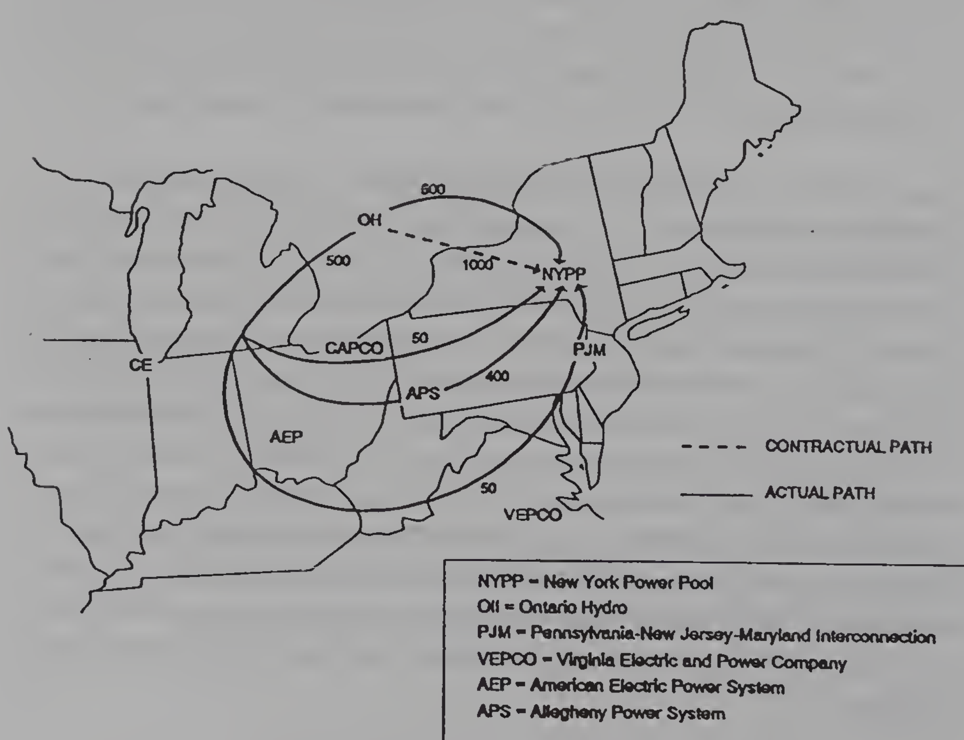


Figure 10. Example of Parallel Path Flow Shipment of 1000 MW from Ontario to New York

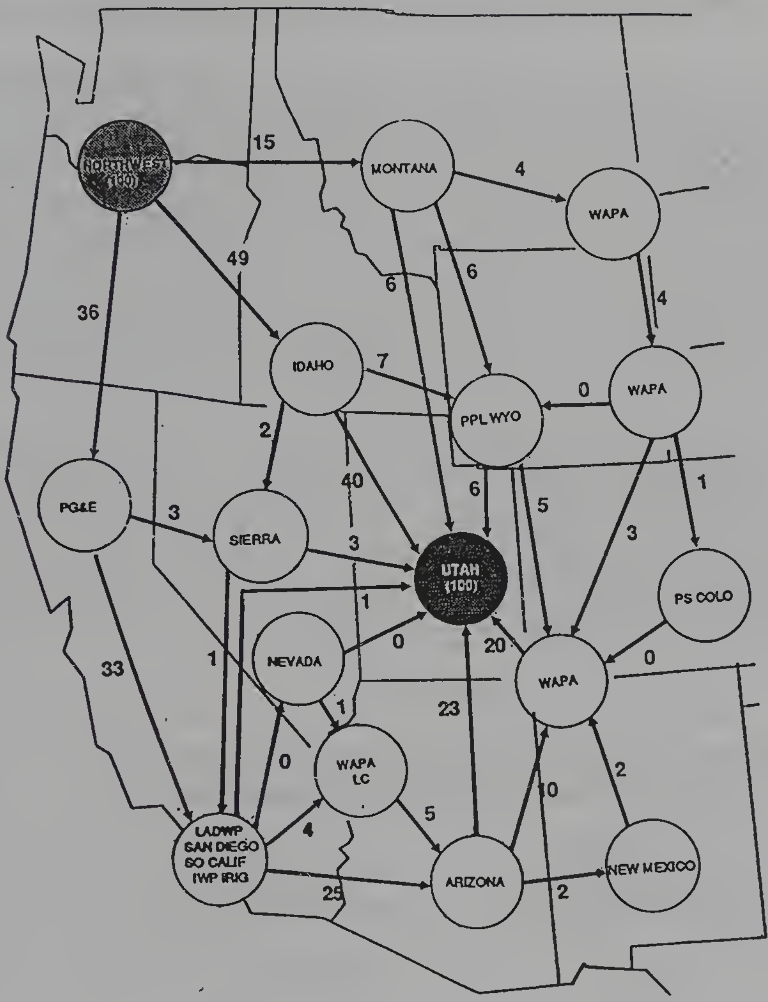


Figure 11. Distribution of Flow for a 100 MW Transfer From Pacific's Northwest Territory to UP& L

In some cases loop flows were the intentional result of network design, reducing the need for additional transmission facilities. In many cases, the combination of loop flow and parallel path flows adversely affected the operation of systems. The solutions to this circulating power problem have not been easy to find. In some cases economic compensation has been used. In others, various control devices, such as phase shifters and operating procedures have been employed. The circulating power problem is still with us today. The ability to directly control the division of power in an ac network, if it ever can be economically achieved, is the only real solution.

The Increasing Importance of Transmission [14]

If history has shown us one thing, it is that the role and importance of transmission in electric power systems increases with the passing of time. The savings in capital that are made possible, the reductions in fuel costs, and the overall savings to the economy of a nation through the use of a good transmission system all continue to grow. Specific data illustrating this for the investor-owned utilities in the U.S. is shown in Table 3 [15]. The energy delivered by interconnections between companies in 1981 was 11 times what it was in 1961, while the total sales to ultimate consumers in 1981 were only slightly more than 3 times what they were in 1961. Increasing interchanges show the growing economic benefits from the available interconnections and increasing coordination between utilities. Recent estimates of the annual savings produced by interregional interconnections in the U.S. are about $20 billion, two-thirds of which result from investment savings due to reduced generating capacity requirements and one-third from fuel cost savings [16][17].

Table 3

COMPARISON OF INERCOMPANY DELIVERIES WITH TOTAL SALES TO CONSUMERS

Year	Intercompany Energy Deliveries		Total Sales To Consumers	
1981	118,641		1,634,217	
1976	70,686		1,417,762	
1971	49,928	11x	1,149,383	3x
1966	21,736		849,043	
1961	10,379		544,931	

Source: Table derived from information from the U.S. Department of Energy, Publication Series 0437 (published every year), Financial Statistics of Selected Electric Utilities.[15]

The U.S. experience, particularly the understanding of the key factors and limitations in developing a transmission system, has provided useful guidance for the development of transmission systems and interconnections in other countries [18][19][20].

The Electric Power System as a Single Machine[4][21][22][23]

Because of the synchronous operation of all its generators, an interconnected electric power system functions as a single large machine which can extend over thousands of miles. One of this machine's characteristics is that changes in any one portion of it instantly affect the operation of all other portions. Future plans for any one part of it can affect other parts of it. The obvious concerns are to what degree planning the addition of a new generator and a new transmission line in one part of the system affects the development of systems' plans 500 and 1,000 miles away.

In system operation the effects of developments in one system can be felt throughout a large geographic area. For example, if a large generating unit is lost in New York City, the interconnected power system (the machine) suddenly has less power input than power output. Any machine in which this occurs will slow down. This is also what happens in electric power systems. As the individual rotors of every generator in this system slow down, each gives up a certain amount of its rotating energy (ω^2 R) to compensate for the lost input from the unit that has tripped.

Instantaneously, with the loss of a large unit, there is an inrush of power from units all over the synchronous network, feeding into the system or region that has lost the generator unit. While these inrushes of power from individual units long distances away are not large, they accumulate and build up like water flowing from creeks into a river, approaching the system which has lost a large unit as a flood.

The very reason that systems have been tied together and operate in synchronism causes this effect. By having the various generator units throughout the region assist with the loss of a large generator unit in a specific system, the total amount of spare or reserve generating capacity required can be reduced. This is similar to the insurance business. The larger the number of policy holders, the better able the insurance company is to cope with any specific major disaster and the less percentage reserves it requires. The great strength of operating in synchronism and being tied together in an integrated system is the ability of one system to be helped by others. Its greatest weakness, however, is that the inrush of power into any one given system can cause transmission system overloads. This demonstrates a principle I learned early in my career -- look at a system's or a procedure's greatest strength to see the source of its greatest weakness.

Because of these characteristics of modern electric power systems, the design and operation of the key elements in the synchronous network must be coordinated. Business decisions, government legislation and regulations, and other institutional processes must be compatible with the technical characteristics. Many problems can be solved by technical solutions or institutional solutions, and in some cases by both.

Maximum Size of an ac System

A key question being asked at the present time and one that will be asked more often in the future is: *How large an ac system, with all units operating in synchronism, is possible?* There are those who feel we should operate all of the generators throughout the world in synchronism by building ties from England to Europe, across Asia, across the Bering Straits, to North America and to South America. The advocates of this concept see other political advantages to such an network. They believe it could be an instrument for worldwide peace and coordination as well as an immediate and frequent demonstration of how what happens in one part of the world affects the rest of the world. They also see economic advantages to this approach. Unfortunately, many of those involved in pursuing this concept are not aware of the technical problems and difficulties associated with a single electric machine supplying the whole world.

My reviews of the feasible size of an ac network have gone on for many years. The following factors must be considered [24]:

- **The problems presented by the differences in their underlying reliability standards and constraints.** With ac systems, problems in one system are inherently passed on to the other synchronized systems. The installation of dc ties between two systems essentially isolates problems in one system from another.

- **The effects of the loss of large units in a given system**. These effects are determined by the size of the synchronous network with which it is linked. The inrush of power over interconnections with loss of a large unit is increased in proportion to the size of the synchronous interconnected network. As more and more ac systems become tied in synchronism, this inrush will increase the amount of unloaded transmission reserves required in the ties between systems. For contingencies such as the loss of a large unit or the loss of a complete power plant, the amount of transmission capacity required internally in the various intervening systems (even those quite remote from the contingency) will beincreased. The basic question is, "Does the increase in the size of the network provide economic benefits to offset these cost increases?"

- **The physical ability to operate and manage such networks.** This is determined by communication requirements, computer requirements, and by the number of operating personnel and the skills required of them.

- **The methods of regulation and control used in each of the systems**. These must be the same. If they are not, significant expenditures may be required to achieve compatibility of the regulating and control equipment and to arrive at uniform operating procedures before ties can be established.

Con Edison's "Big Alice"

A specific example of the working of the "single machine" can be seen in Consolidated Edison's (Con Edison's) decision to add a 1,000-MW unit (called Big Alice, because it was derived from the fact that the generator was the largest, and last, generator manufactured by the Allis Chalmers Corporation) about 30 years ago. One reason Con Edison selected this size unit was to counter its reputation for lacking innovation [25]. They hoped that the installation of the largest single generator unit in the United States would change their image as a backward, conservative, and poorly-managed utility. The favorable publicity was a key factor in their decision. They moved forward with the decision to install this large unit without adequate study of the power inrush problem and failed to inform the neighboring utilities of their plans before they were consummated. Their management also failed to realize that the electric power system is a single machine.

After the companies in the surrounding regions learned of Con Edison's plans, they studied the potential impact of the loss of this 1,000-MW unit in Con Edison on their systems. They discovered it would cause severe overloading in lines as far west as Ohio and Pennsylvania. These loadings were severe enough that, if the loss of the large unit occurred at certain times, transmission circuits could be overheated and possibly burn down.

The systems whose transmission circuits would be at risk because of Con Edison's addition of "Big Alice" were very concerned and upset.

I was present at a high level meeting with top officials from the various systems. The situation was described to Con Edison and the technical facts were not disputed. The external systems asked Con Edison to limit the output of "Big Alice" to a maximum of 600 MW until the necessary transmission system changes could be made. At first they were very reluctant to do so, since it meant that a significant portion of their investment in this unit could not be used for a number of years. When they balked at this proposal, they were presented with an alternative. All the tie lines to Con Edison would be opened leaving New York City out of the synchronized grid. It would no longer be part of the single machine. This would leave the city with many problems because emergency assistance from external systems would no longer be available. Faced with this institutional alternative, Con Edison reluctantly agreed to limit the output to 600 MW.

Because we were not sure of the ability of Con Edison to operate as they had agreed, at my recommendation PSE&G also installed technical protection. Relays were installed on a key transmission circuit feeding into New York via Staten Island from New Jersey. These relays were set to trip the key tie from the west into New York City if Con Edison did not limit the inrush of power by providing sufficient spinning reserves to reduce the tie loading fast enough to prevent burndown of transmission circuits in other systems.

Here, we have an example of the need for institutional and technical solutions that are coordinated and workable. These solutions need to recognize that the electric power system is a single machine and that generation and transmission are integrally related. Institutional policy cannot be set without full recognition of all of these factors.

Chapter 2
A CHANGING WORLD AND ITS NEEDS

The Golden Age

The golden age of electric utilities was the period from 1945 to 1965. During this period there was exponential load growth accompanied by continual cost reductions. New and larger plants were being installed at a lower cost per kilowatt. Improvements in efficiency were being obtained through higher temperatures and pressures for the steam cycle, which was lowering the amount of fuel required to produce a kilowatt hour of electric energy. New generating plants were being located at the mine mouth where coal was cheap, and power was transmitted to the load centers. This required new, higher voltage transmission lines since it had been found that "coal by wire" was cheaper than the existing railroad rates.

The coordination of utilities was at a maximum. The leaders of the industry involved in planning the power systems saw the great advantage of interconnecting utilities to reduce capital investments and fuel costs. Regional and inter-regional planning organizations were established. The utilities began to see the advantage of sharing risk by having jointly-owned units.

On the analytical side, improved tools were rapidly being developed. Greatly improved tools for technical analysis -- such as computers -- began to appear, first as analog computers and then as digital computers. At the same time, the first corporate models were developed for analyzing future plans from the viewpoint of cost to the customer, the need for additional financing, and the impact on rate changes.

All of these steps reduced capital and fuel costs which resulted in lower rates. Everyone was happy. The customers were happy because the price of electricity was going down. The investors were happy because their returns on investments and the value of their stock were increasing. The system engineers were happy, because they were working on interesting and challenging problems which were producing recognized benefits, and their value to the utility organizations was increasing. Finally, the business managers were happy that they were running organizations which were functioning smoothly and were selling their product to satisfied customers.

Blackouts and the Reliability Crisis

The first blow to this "golden age" was the blackout of New York City and most of the Northeast, in 1965, which was caused by events taking place hundreds of miles away. The "single machine" had a major breakdown. While it was able to withstand far more contingencies than the former isolated systems, it had suffered a more massive collapse when highly unlikely failures occurred.

For the first time those designing and operating the power systems, those managing them, and those investing in them began to realize that their systems were vulnerable to extensive collapse. Government officials were very concerned with the socio-economic costs -- the impact on people, on the productivity of the state, on the physically ill and handicapped, on those riding subway trains, etc. These became of grave political concern. The public was upset. How could engineers design such weak power systems that could collapse over several states? This event stressed how important it was for engineers to recognize the potential impact of all possible failures of the systems they design.

The engineers were concerned, too. They were concerned with the cause of collapse and how to minimize the probability of future collapses. Another concern was with the inordinately long time, the many hours, it had taken to restore all service after the collapse. An electric system which depends on its own electric power for restarting was obviously a flawed concept. Yet, this is what the engineers had developed in New York City.

The government reaction was immediate. Joseph C. Swidler was then Chairman of the Federal Power Commission. On order from President Johnson, he set up investigative teams to look into the prevention of future blackouts. These teams toured the country and looked at the many potential causes and risks in various regions. As a result, they wrote an excellent report called "Prevention of Power Failures" [26] which is a classic to this day. Unfortunately, much of the advice in the report has been forgotten by those in utility management and by those in government in the 25 years since the New York blackout [27][28].

Joseph C. Swidler -
The Motivator to Voluntary Cooperation

I am not an admirer of most lawyers involved in utility regulation. There is one, however, whom I hold in the highest regard -- Joseph C. Swidler. He had the ability to motivate the electric utilities he regulated to voluntarily move in directions called for by the public interest. He was able to gain utility participation and significant personnel contributions for many activities, thus obtaining the best qualified talent at minimum cost to the government.

I first met Joseph Swidler when he was Chairman of the Federal Commission. I will always recall the talk he gave in San Diego at an EEI meeting calling on the electric utility industry to become far more active in developing research programs. This speech provided the impetus that lead to the founding of the Electric Power Research Institute. I also met Joe Swidler when he was Chairman of the New York State Public Service Commission and afterward when he returned to Washington to practice law.

Joe Swidler, though a lawyer, was really an engineer at heart. I have never met any other attorney who had a clearer understanding of electric power systems, their technical functioning, their economics, the factors that affected their reliability, the consequences of disruptions to the public welfare, and other key factors. Joe Swidler helped me understand the need to consider the institutional and political problems thoroughly when developing technical solutions. His very clear understanding of the functioning of government, the regulatory system, and the political means of achieving desired technical and economic objectives in the development of power systems has been invaluable. To this day, I still enjoy meeting with Joe. His lively mind provides views on U.S. regulatory developments, the electric power situation in Europe, or the ways to solve our own national problems. His perspective in these areas is priceless.

I was more personally and more intimately involved in a second major blackout, the PJM blackout of 1967 which caused power to be interrupted in all or portions of four states. The day after the blackout occurred, the governor of New Jersey convened a delegation of officials from the various utilities in his office. We were told that the blackout had done major harm to the economic development of the state and, while he was not going to tell us how to do it, we had to take steps to prevent such a blackout from ever occurring again. When we returned to our offices, I was put in charge of the investigation, including analytical recreation of the blackout. As a result of this work, Public Service developed a $30 million program to make changes in its system, power plants, and substations that would reduce the probability of such future interruptions and speed the restoration of service if they did occur.

Subsequently, the New Jersey Public Service Commission made, on its own, a number of analyses. Similar analyses were made in other states. A meeting was called in Philadelphia by Bill Doub, then Chairman of the Maryland Commission, where the chairman or president of each of the state commissions met with the chief executives of each utility involved. At this meeting, the heads of utility commissions stated that they were convinced that part of the problem had been the underforecast of load, and that the utilities were continuing to forecast their load too low. Feeling they had to take some political action, they mandated that several thousand megawatts of generation be added to the system to minimize the probability of future blackouts. The utilities compromised by agreeing to put in about one half the mandated amount. This was about 1000 MW for my company, Public Service Electric and Gas.

These recommendations made by the regulators did not recognize the root cause of the problem. The blackout resulted from transmission inadequacies, not a shortage of generation. Adding generating capacity was not the proper solution. Those familiar with power systems know that there has never been a widespread blackout during times of generation shortages. Blackouts are generally caused by major perturbations (usually the sudden occurence of faults causing major disturbances), or sudden changes in available system facilities or conditions, not by the shortage of generating capacity. Such perturbations can be simultaneous faults, incorrect operation of protection systems, etc. Once such a perturbation has occurred, it can result in cascading outages. This is when the loss of one facility causes an overload in another, producing its subsequent loss, and then is followed by additional circuit losses. Such cascading outages cause the power system, the single machine, to split into electrical islands. In cases where the load of the island exceeds the generation, the system will slow down and, as the frequency declines, generators will be tripped to protect them from damage. The end result is a complete interruption of a major portion of the system, sometimes affecting several states.

It is important to note in this present era of "prudence," where utilities are repeatedly accused of overforecasting loads and installing excess capacity, that not too long ago the opposite claim was being made by the regulators. It is also interesting to note that the generating capacity installed as a result of this mandate was subsequently found to be excessive by the regulators who replaced those who had issued the mandate. Because of instances such as these, many of us have felt through the years that regulatory competence is sadly lacking.

As a result of these blackouts, it became apparent that both institutional and technical changes were needed to reduce the probability of future large scale outages.

Institutional Solutions -- the Formation of Reliability Councils and NERC

Simultaneous with the government-sponsored reviews, the Edison Electric Institute's System Planning Subcommittee met in February, 1966 in St. Petersburg, Florida. At this meeting of 12 people, which included myself and Ted Nagel, the steps that the electric power industry had to take to minimize the cause of blackouts were discussed extensively.

It was apparent that the prime cause of the New York City blackout was that the electric power system was a "single machine" extending over a large geographic area and that coordination of its design and operation was lacking. Company A had no control over the actions or lack of action, of Companies B, C, and D that affected its reliability. It was agreed to establish an organization that would provide some control over the way individual companies operated and planned their systems since they could affect the reliability of other systems. This suggested a number of regional "reliability councils" under an umbrella of a national organization which would subsequently be called the North American Electric Reliability

Council (NERC). These organizations should provide a voluntary mechanism for monitoring the electric utilities of all types: investor-owned, government-owned, municipally-owned, cooperatively-owned, etc., to insure their compliance with a reasonable set of planning and operating criteria.

Ted Nagel - The Inventor of Institutional Approaches

Through many years of my career, I was fortunate to be associated with Ted Nagel. Ted was in charge of planning for the American Electric Power Company (AEP), while I was in charge of planning for the Public Service Electric and Gas Company. Although AEP was in the midwest and Public Service was in New Jersey, Ted and I lived within a few miles of each other in New Jersey (since AEP corporate headquarters were in New York). We first met through Edison Electric Institute (EEI) activities where Ted and I were active. Later on, we both served on the NERC Interregional Review Subcommittee which reviewed the transmission plans and the conditions of electric power systems throughout the United States several times a year. Ted was Chairman of the Subcommittee, and I was one of the members.

Ted helped me gain an understanding of electric power systems throughout the U.S. and worldwide. He had an outstanding breadth of knowledge, and his close association with Philip Sporn (who, for many years, was President of AEP and an outstanding engineering pioneer within the electrical utility industry) was extremely valuable. At a meeting in St. Petersburg, Florida in February of 1966 in the wake of the Northeast blackout of 1965, the EEI System Planning Committee,under Ted's leadership, concluded that the U.S. needed an organization to ensure the reliability of the complex transmission networks being created. The organization formed to achieve this was NERC. Working with Ted Nagle, I became very involved in CICRE activities. Together with Charles Concordia, we provided a large part of the U.S. representation in world technology exchanges through the CIGRE Planning and Operating Committee.

I will always remember the Sunday afternoons when my phone would ring and Ted Nagle would say something like, "Jack, I am sitting out on my back deck and working on a draft of this report on establishing the reliability criteria under NERC. I would like to talk to you about it if you have a chance. Can you come up?" Frequently, I would go up an spend the Sunday afternoon talking with Ted. This opportunity to interface with a man of Ted's caliber while sitting in a garden, in relaxed circumstances, provided a means of reviewing, thinking, and creating that played a very important role in my life.

During this meeting, the question was raised as to whether or not these monitoring and control functions should be performed by the government or by utilities. The view was unanimous that the government did not have the competence to do this. This monitoring had to be done by the professionals: the engineers and the managers responsible for the design and operation of these systems. It was also recognized, however, that if this were not done voluntarily by the industry, the government would step into the void and create bureaucratic controls which would not solve the reliability problem and could very conceivably complicate it. The lack of technical competence within the governmental bureaucracies at all levels, state and federal, as well as the lack of governmental understanding of the technology and the economics of power systems was of grave concern.

As a result, steps were taken to establish reliability councils in the various regions of the United States, and to establish the National Electric Reliability Council to coordinate the various regions. Later renamed the North American Electric Reliability Council, to recognize participation by Canadas' utilities, this organization still exists today. In retrospect, while NERC has many imperfections, there is no question that the path taken was the right one. Organizations involved in technical operations and decisions need to voluntarily coordinate to achieve the public interest. The government role should be limited to oversight rather than direct involvement.

Technical Solutions

Three principal technical steps were seen by utility engineers as vital to blackout prevention:

- Strengthen the then-existing weak transmission systems in some regions of the country to reduce the probability of cascading transmission outages.
- Install under-frequency relaying to shed load quickly as system frequency declined so as to limit the extent of the interruption in the unlikely event that cascading outages would occur.
- Provide "blackstart" capability for generators in the event of a complete system shutdown, i.e., the ability to restart generators without any electricity available.

As a result, major transmission reinforcements were made in the following ten-year period; under-frequency relaying was installed throughout the interconnected power network; and blackstart capability was provided in many power plants.

Underfrequency Relaying

The blackout investigations also lead to the realization that when the very large and complex machine which constituted the power system began to have problems, to oscillate, and to go into turbulence, different symptoms appeared in different portions of the geography affected. The ability of the human operators in the control centers to act correctly during these disturbances was questionable. Particularly questionable was their willingness to interrupt loads when the system capacity was exceeded and the entire machine was slowing down (i.e., the frequency was declining). These system operators had been trained all their lives to maintain service, keep the system working, and protect equipment. The interconnections between systems are somewhat analogous to the rope that connects mountain climbers. The objective of this rope is to provide a means for those who have stable footholds to help someone who has slipped and would fall if not for the rope connecting them to the other climbers. The tie-lines between utilities were put there for similar reasons. The utility system operator has just as much difficulty shedding load during system perturbations as a mountain climber would have in cutting the rope to let another climber fall to his death in the case of an emergency.

It became evident that the human operator was not always able to, or capable of, taking the necessary emergency steps during disturbances, and in some cases, did not have adequate information to make such decisions. The obvious solution was to install automatic means in the form of "underfrequency relays." These relays would be set on certain loads throughout the networks and would shed the load as the frequency began to decline, bringing back a balance between the generating sources available and the power to be supplied. By shedding load, the deceleration of the system could be halted and normal frequency restored. This would be a first step in restoring the system to normal and in preventing a massive cascading outage and a complete system blackout. It was agreed that "amputation" of a portion of the system was preferable to a complete system shutdown.

A problem arose with this development, however, in that the various systems began to install relays having different settings. One would install relays that would shed 20% of its load at 59.6 Hz (cycles per second); another would shed the first 10% at 59.3 Hz; similarly with the subsequent steps in load shedding. Such an arrangement was not desirable for systems operating in synchronism and always having the same frequency, since load could be shed excessively in some systems and not at all in others, and load would be shed in one system while the problem was in another.

This problem came to the attention of the EEI System Control and Protection Subcommittee during my term as chairman. We decided that a meeting was necessary to emphasize the need for consistency and coordination in setting these under-frequency relays. The System Control and Protection subcommittee met in Detroit and a number of presentations were made, one most noteworthy by Charles Concordia, who was viewed with great respect by all attending. Dr. Concordia emphasized the need for consistent relaying settings. Gradually, through the EEI and sub-sequently through NERC, basic frequency settings for load interruption of 59.3Hz, 58.9Hz, and 58.5 cycles were adopted.

Islandizing Relays

With the decision to install underfrequency relaying to shed load, there was considerable attention given to using underfrequency relaying to open ties and to islandize portions of systems. The theory was that by islandizing portions of systems in which generation and load were balanced, some of the system could be saved even if the most massive contingencies occurred.

The general view, however, was that no system in the network should start islandizing portions of its system until the collapse of the system was inevitable. Studies concluded that when a frequency of 58.0 Hz was reached and maintained for at least five seconds, the collapse of the system was imminent and everyone should be free to save themselves. If systems opened their ties to "islandize" prior to this point, it could significantly increase the possibility of a complete system collapse when such a collapse would not occur if the systems remained tied and provided emergency support to each other. After the conclusion was reached that 58 Hz was the "abandon ship" frequency, each of the systems was free to develop its relaying and protection for tripping lines and for islandizing within itself.

Studies were made by Public Service Electric and Gas and complete plans were arrived at for establishing the various potential islands and the boundary points where the islandization would occur. We contemplated splitting into six islands, each of which had the potential to survive if the entire system was going down. Appropriations were approved for this plan.

I began, however, to have further concerns about the islandizing schemes. They were complicated and required a considerable amount of interrelated relaying and controls. What if they did not function properly? What if they malfunctioned under normal conditions? Could they cause more problems then they were designed to prevent? These were questions that were not amenable to detailed mathematical analysis. They depended on judgement. After considerable thought, I concluded that the installation of the islandizing relays on the Public Service system, which would be quite expensive, was not justified. As a result, I recommended the entire concept be dropped. This was, indeed, a bitter pill to swallow -- since I had proposed the concept to begin with -- but I believe it demonstrates the need to continually review technical recommendations and solutions that one is proposing and to repeatedly mull them over in one's mind. Only through this process can one exercise the judgement that is necessary when complex technical design decisions are made. The correctness of this decision was demonstrated by a complete blackout in France in 1978. Islandizing relays had been installed through a number of regions in the country and were partly to blame for the blackout.

Blackstart Capability

Even though major steps were taken to reduce the probability of blackouts, additional plans were made to reduce restoration times if the unlikely should occur. At PSE&G this included the installation of facilities at all generating stations to allow the starting of the plant without any external sources of power. In some cases this required the addition of small diesel generator units. In others, existing gas turbines were modified so that pressure in the gas supply lines would start the unit.

Much supervisory control was also installed so that the circuit breakers on the transmission system could be opened and closed from remote locations as the generator units were started.

The Need for Research - the Formation of EPRI

Coincident with the development of voluntary organizations to govern the action of utilities from a reliability viewpoint, efforts were underway in the early 1970s to increase the research activities of electric utilities. Joseph C. Swidler, in a speech to several thousand members of the electric utility management at the 1970 EEI convention in San Diego, laid down a challenge to the electric power industry. There was a great need for increased research in all aspects of electric power systems, from the application of new technologies to the control of the systems. He felt this was not being done and his challenge to the utilities was that they initiate this research, or else the government would have to step in. The obvious reaction on the part of the industry was, again, *"Let's get going on this!"*

Sharing this concern was Edwin H. Snyder, the Chairman of the Board at PSE&G and then Chairman of the Electric Research Council. While PSE&G had tried to do research on its own, and EEI had tried as well, the failure to have an industry-wide approach to the necessary research was handicapping these efforts. It was difficult to raise the funds needed for large projects on an individual company basis. It was equally difficult to organize the management to control the research without some type of umbrella organization. Ed Snyder agreed that we had to move forward with an organized, industry-wide research program. Meeting with Raymond Huse and myself, he proposed to contact the chief executives of half a dozen other electric utilities, whom he knew personally, and to present the idea of establishing a task force to study industry-wide research needs and the possible organizational arrangements for accomplishing them.

He called the chief executives of Con Edison, the Philadelphia Electric Company, Pennsylvania Power & Light Company, General Public Utilities Company, some of the New England companies, and companies in the Midwest. The reaction of this group was cautious. They did not see the urgency for research. Ed Snyder discussed this with us and we told him we did not agree with this view. There was a real need for research, and it was not being done by the existing industry structures. He proceeded to call a number of these people back and he told them they were faced with a choice of cooperating with this effort or standing by while the government took over the research that would determine the future of their organizations. Realizing that government intervention was imminent lead them to agree to participate. PSE&G would furnish the leadership and staffing for this task force and they would each provide a member. He turned to me and said, "Can you let Ray Huse go for a year or two for this activity?"

Ray had been directing the research activities in PSE&G under my management, and I was glad to volunteer him. As a result, in 1971, the Goals Task Force produced a report outlining the industry's research needs and describing an organization which became what is today the Electric Power Research Institute (EPRI). Further, as a result of this report, the bulk of the industry became more cooperative in supporting the new organization, funding procedures were developed, and EPRI was founded in 1972.

One of the initial tasks in forming EPRI was to select a nationally-known individual as president who would organize the staff and initiate the entire operation. The industry executives decided that an outside individual be chosen for this top job. The first two individuals contacted to head EPRI turned the job down. Dr. Chauncey Starr, the third choice, accepted. He picked his own aides and, unfortunately some of his selections were not particularly knowledgeable of the electric power industry or of its problems. While EPRI has had some successes, the amount of money they spent in the past compared to the results they achieved has been questioned by many in the industry and in government. Fortunately, under current leadership, EPRI appears to be achieving better results.

The Environmental Crisis - The Shift to Low Sulphur Oil

Starting shortly after the reliability crisis, and overlapping it considerably, was the environmental crisis. Both the public and the government became concerned about air quality, water quality, and the effect of electricity production on the environment. The initial solutions -- which were rather obvious -- called for the installation of nuclear units (which essentially had no exhaust); converting some of the existing coal-burning units to low-sulfur oil; providing electrostatic precipitators to filter out particulate emissions; and installing cooling towers so rivers would not heat up. All of these steps were readily accepted by most utilities, significantly increasing capital costs and fuel costs.

The Fuel Crisis - The Shift From Oil

While these changes and additions were still underway, they were overtaken once again by another crisis. The OPEC organization stopped selling oil to the United States. This caused immediate problems. The day after the oil embargo was declared, a number of us were called to Washington to meet with a group of government officials and determine what should be done. The overall decision was to use the existing oil supplies to keep U.S. industry going. This was essential for the stability of the national economy. Less essential activities, including the use of energy in commercial areas and shopping centers, and the use of energy in individual residences, were selected for the more severe cuts.

In addition, it was decided that those utilities with fuel reserves in on-site storage should share them with other utilities. This sharing of oil reserves by one generating company for use in another was only possible because of the interconnections existing between systems and regions which had been designed for generation capacity emergencies. This procedure raised questions, however, since those who had been wise enough to provide the reserves had incurred costs to do so -- costs paid for by their customers. This action would result in the benefits of their financial commitments being enjoyed by others who were not as wise. Overall national interest predominated, however.

This procedure had a long-term negative effect. It led many in the utility industry to believe that if you take risks and make investments intended to benefit your stockholders and your consumers, the government can always step in and take the significant benefits that may accrue from these investments and force you to share them with others. This has been a basic problem with the electric utility industry -- the sharing of benefits among all, when the investments involved were made by a few.

As a result of the oil crisis, President Nixon's administration initiated "Project Independence" which called for the United States to reduce the amounts of oil and gas used for producing electricity by shifting to domestic energy resources such as coal and nuclear energy. Under the Carter administration, the emphasis was placed on energy conservation. As a result, in 1978, the Public Utilities Regulatory Policy Act (PURPA) legislation was passed. Its purpose was to improve the efficiency of use of energy in two ways: (1) encourage co-generation in which both steam and electricity, or mechanical power and electricity, would be produced in the same plant; and (2) foster the development of "small power producers," using refuse or other natural products as fuel (with low head hydro power also qualifying under this umbrella).

Out of the oil crisis, and the large differences in fuel costs that resulted, came the strong impetus to build nuclear plants with commitments made by many utilities. For many years, oil, coal and gas had costs that were quite close to each other. As a result of the OPEC policies and the oil embargo, oil costs were suddenly much higher than those of coal and gas. Fuel costs rose significantly in some regions. The transmission system was used increasingly to ship energy from coal generating resources in one region to other regions heavily dependent on oil. Some of these energy transfers took place during the off-peak hours -- the nights and weekends -- but some of them occurred during heavy load times. The oil embargo led to a change in the way transmission systems were used. Prior to that, they had been used predominantly to reduce the amount of generating capacity needed, thus saving capital costs. This change of use lead to significantly different loading patterns, loading patterns for which the transmission systems were not always designed.

The Financial Crisis

After these three crises, following in sequence with overlaps, came a fourth -- the financial crisis. The result of the blackouts, the environmental crisis, and the fuel crisis had been to raise electric power costs significantly. At the same time, the country found itself in an inflationary spiral, with the cost of money (which is the "true" cost of money of about 3% or 4%, plus the inflation rate) beginning to increase rapidly. All utility costs escalated, requiring large rate hikes. Because of the political impacts of such rate hikes, the state regulatory commissions rejected many of the needed rate increases, thus exacerbating the financial problems of utilities. In addition, the increases that were allowed, while not sufficient to keep the electric utility industry financially healthy, were significant enough to cause some elasticity effects: due to the rise in prices, the use of electricity decreased. The financial crisis resulted in a period of increasing costs, declining revenue, a sharp reduction in load growth, and large amounts of generating capacity under construction that would not be needed as soon as originally projected. Since a large amount of this generation construction was nuclear, the crisis caused a delay in the construction and completion of many nuclear plants. This delay amplified the financial crisis even further because there was an appreciable investment in these partially completed plants on which interest had to be earned, even though the plants were not operating or producing any electricity.

At about the same time, the Federal Government had become very chaotic and unpredictable in the regulations it issued for the construction of nuclear plants. Almost weekly, new safety requirements were published by the Nuclear Regulatory Commission requiring a change in the design of these plants while they were already under construction. There is no question that a great deal of costs incurred for U.S. nuclear plants were a result of the erratic and inconsistent behavior of the Federal Government. It is not possible to build a nuclear plant, which involves several thousand people on site for a number of years, without having stable requirements for the design. The design cannot be changed while the construction is in progress without causing significant increases in cost, and worse yet, increasing the safety risks resulting from "patchwork" changes. In the United States, we failed to imitate the French who have completed a very successful nuclear expansion program, using -- for the most part -- U.S. technology. In France, the regulations that exist at the start of construction are not changed during the construction. If new regulations are issued, they apply only to the new construction.

At this time, there were many who believed that spending money to reduce peak consumption was more economical than using it to build new generating and transmission capacity. This concept has been called "least-cost," "demand-side," or "integrated resource" planning. Unfortunately, some of the benefits that have been projected for least-cost planning have not yet materialized and may never do so. This is not to say there are not some economic benefits from least-cost planning -- but some of the claims have been excessive.

All of these events led to higher and higher generating capacity margins, and to charges of imprudence on the part of utility managements. The state regulatory commissions began to initiate "prudency audits" in which they reviewed the decisions of the utilities to build certain power plants, the construction management of these plants, the cost controls put in place, and the costs of replacement power which had to be obtained because of delays in construction. These prudency reviews became a mechanism for funding a great deal of consulting and legal work, and in some cases, were designed to make the utility commission members appear as heroes.

The Legislative and Regulatory Crisis

The most recent and presently continuing crisis, triggered by the financial difficulties and the prudency audits, is the regulatory crisis. Some seeds of the regulatory crisis were sown in actions taken by the Federal government. The PURPA legislation passed in 1978 prescribed the use of "avoided costs" for determining payments to co-generators and qualifying facilities (QFs), such as low-head hydro and garbage burners. These "avoided costs" were the alternate utility costs for producing electricity based on the alternates available to the utility system. They were also usually based on a short-term view. This procedure contradicted the basic planning philosophy that alternate energy sources should be selected based on a long-term view, not a short-term view of the total system. The avoided-cost approach led to a short-term view and to very excessive payments to some co-generators and other qualifying facilities. Some even received returns on investments in excess of 100% a year.

The California Public Utility Commission has evaluated what its own rules cost customers of the Pacific Gas & Electric Company in a one-year period compared to the utility operating its system using the lowest cost power supply available. Since the utilities have been forced to purchase power from these co-generators and QFs. They were buying at precommitted avoided costs when many hours of the year they could buy from other sources or produce it themselves at lower costs. The California Public Utility Commission Study showed that the penalty to the customers of PG&E from the Commission's own rules was more than a billion dollars in one year[29]. It shows, again, what a lack of technical and economic competence in the legislative and regulatory areas can lead to in terms of harm to the public. It also shows why our institutional solutions and technical solutions must be coordinated and developed by knowledgeable individuals.

The next step by the various regulatory commissions was the proposal, and in some cases the adoption, of competitive bidding procedures. These are procedures under which all potential suppliers of electricity submit their bids in response to requests from the utilities which need additional generating capacity. This approach is currently under development and has many flaws. Particularly difficult is the proper evaluation of various bids on a long-term and regional basis.

During this same period, the Federal Government issued a series of NOPRs (Notices of Proposed Rulemaking), which caused great debate and much chaos with very little progress. In my opinion, the Federal Energy Regulatory Commission's competence and understanding of the problem, both at the Commission level and at the staff level, was very poor. The key reason for this was that the appointments to the Commission were based on political considerations and pressure groups, rather than on the knowledge and competence of the individuals. Particularly harmful was the period of time when the Commission was headed by Martha Hesse. The difficulties with the management and administration during her tenure were reported by FERC commissioners, Stalon and Trabandt in a hearing before Congress [30]:

> *...The FERC has an elaborate staff and an elaborate division of labor, but it is very short on mechanisms for bringing that knowledge to the minds of the decision makers at the time the decision has been made.* (Stalon)

> *...The Department of Energy Organization Act does provide the chairman with responsibility over management and administration, but I don't think that the Congress ever contemplated that that would mean there would be an interruption in the flow of communication between the Commission as a collegial body, the individual Commissioners, and the staff.* (Trabrandt)

> *. . .Currently my understanding is my staff cannot get an answer to any question without the prior approval of the chairman and I think that is unfortunate.* (Trabandt)

> *. . .I would never have any objection to there being a review process for work product. But, where I do object is where there is factual information, analysis, and legal information that is available to staff, but essentially is not made available to the Commission in the decision-making process.* (Trabandt)

In addition, many of the competent engineers on the FERC staff were not available to help the other commissioners, leaving mainly attorneys and economists with very little knowledge of electric power systems.

The utilities are currently moving in a number of different directions at the same time. Some utilities are looking at the possibility of mergers. There is little question that we have too many electric utilities in the United States; mergers could resolve this problem. Mergers, however, are difficult because those managing existing companies, which would be ab-sorbed by the merger, realize their positions of power may be eliminated. Also, mergers require embarking on a long, arduous, and uncertain journey of obtaining the necessary state and federal regulatory approvals.

The other side of the coin is the attempt by some of the companies to split their operations between generation and transmission, perhaps forming separate companies. Because of the strong interrelationship between generation and transmission costs, planning, and operation, this approach is often suggested by those who do not fully understand the complexities, and inherent inefficiencies, this will introduce.

The Future

New technology is under development to help control the loading of individual ac power flows. New Federal legislation has recently been adopted that can affect the use, planning, operation, and design of electric power transmission systems. These are discussed in Chapter 5.

Chapter 3
THE EVOLUTION OF TECHNOLOGY AND INSTITUTIONAL ARRANGEMENTS

The achievement of economic and reliability benefits from electric power transmission systems in a changing world required a great deal of creativity and hard work on the part of electric power system engineers. This effort produced both the new technology and the new institutions that were needed. This chapter outlines the innovative developments that are helping to produce vast savings to our economy and describes how people working together can bring about major technical and institutional change.

Development of Transmission Technology

Transmission technology has evolved since 1882 when the first dc circuits were placed in service in New York City from Pearl Street Generating Station to supply loads in lower Manhattan. This technology was originally dc, but ac quickly became the dominant means of power transmission because of the ability to change voltage up or down through the use of transformers.

Higher Voltages

Through the history of electric power from 1882 forward, the major emphasis in transmission technology was on the development of higher and higher ac voltages. These voltages increased to 138 kV, 161 kV, 230 kV, 287 kV, 345 kV, and 500 kV, and ultimately to 765 kV in the U.S. The development of hardware and equipment for these higher voltages required a considerable amount of research and risk taking in developing the transformers, circuit breakers, insulators and other components needed to transmit power at these higher voltages. The insulation requirements became difficult, particularly because of the voltage surges that occurred during lightning strikes, switching of circuits, and faults. With these higher voltages, problems of radio interference, corona losses and other factors also became important.

The ability to develop, design and build higher and higher voltage transmission equipment was a remarkable achievement of cooperation between the U.S. and other countries. In the U.S., the credit for the development of these higher voltages lays with a few pioneering organizations and individuals. Leaders among the manufacturers were General Electric Company and Westinghouse. Among the utilities, the American Electric Power System, Virginia Electric and Power, and the Tennessee Valley Authority were also instrumental. Throughout much of this, Philip Sporn of American Electric Power provided the driving impetus to move forward with increasingly higher voltages [31]. Today, the American Electric Power System still pays a key role in positioning U.S. utilities for the next step-up in transmission voltages, into the 1,000 - 1,500-kV range [32].

Conductors and Cables

As transmission voltages rose, it was necessary to install electric transmission lines on poles or towers where adequate spacing between conductors and structures would provide the insulation necessary to isolate phases from each other and ground. There became a need for conductors with a higher current capacity. These two forces led to the development of new conductors and to the use of several conductors bound in a group called "bundle conductors" to expand the effective diameter and reduce corona loss and radio interference. Also, by going to larger conductors and by using strands of steel reinforcements in the center of the conductor to achieve mechanical strength, it was possible to provide greater current capacity and conductor strength. Again, this development required pioneering and inventiveness.

In cities, however, the installation of overhead lines was often not feasible; nor was it generally acceptable to the public. The development of high voltage cables became essential. The key problems were the insulation medium and the dissipation of heat. The insulation medium had to be flexible so that the cable could be bent as needed. Special papers impregnated with oil were used. It was soon learned that destructive ionization would take place in any voids that occurred in the insulation. The solution to this problem was to keep a pressure on the insulation. Early attempts provided a porous tube filled with oil under pressure in the center of the conductor. Later the cable (three separate phases) was installed in a pipe (typically eight inches in diameter) which, after careful evacuation, was filled with gas or oil that was maintained under pressure. The use of oil was found to have advantages and oil-filled pipe cables predominate today.

Improved Protection

Because faults and short circuits occur from time to time on electric transmission systems, system protection techniques have been used since the earliest days to disconnect the faulted equipment, and allow the remainder of the network to continue operation. This has been accomplished through the use of relays, which sense the existence of such faults, and send an appropriate signal to circuit breakers that disconnected the faulted line or apparatus. Relays have also been used to stabilize system conditions resulting from various types of perturbations. A brief summary of the evolution of system protection techniques is given in Table 4 on the following page.

Since transmission lines are predominantly carried overhead on towers, they are subject to lightning and other external forces. To protect these lines from damage and to ensure their reliable operation required significant improvements in protective devices for lightning strokes. New lightning arresters and new methods of grounding lines were developed to reduce the magnitude of over-voltages resulting from "traveling waves."[33]

To protect against faults or short circuits, new types of circuit breakers and relaying protection were developed. The speed with which the disturbance could be removed from the system was of vital importance. As the protection system became more important, it also became apparent that a failure in the protection system was a contingency that had to be considered in developing the system. System layouts and designs were developed so that a circuit breaker or a relay could fail, and the system would go on working.

TABLE 4
Evolution of System Protection Methods

DATE	MILESTONE	NEW TECHNIQUE	ADVANTAGES
1900s to 1960s	Electromechanical relays	1900s - Overcurrent 1940s - Differential 1950s - Impedance	Relay settings were determined in advance. Relay setting could be changed by utility personnel.
1960s	Under frequency relays	New types of relays developed and installed. Included needed time delays to coordinate with other requirements. Also rate of change of frequency relays developed.	Provided for designed load reductions during periods of declining frequency to limit the frequency reduction.
1970s	Digital relays	Digitally performed same functions as electromechanical relays.	Reduced costs for "hard wiring." Settings and testing made easier.
1980s	Digital relays (active)	Relays programmed to calculate new settings when system changes occur. Relays programmed to automatically test relay functioning and setting.	Significant improvement in the overall reliability of relaying protection.
1980s	Fiber optics	Provided internal control wiring of greater capability and free from electric and magnetic field disturbances.	Improvement in capability and reliability.

The Coordination Between Equipment and System Designers

This provision for "stuck breakers," relaying failures, bus failures etc., required close coordination and cooperation between those developing and designing the equipment and those designing the systems. This close coordination between system designers and equipment developers led to the development of circuit breakers that could clear faults in two or three cycles. This made possible increased stability limits on systems so that they could transmit more power.

Incremental Cost Dispatch

Electric power systems are different from other systems in that the product must be manufactured the instant it is needed. There is essentially no way to store electricity economically, outside of a few pumped storage plants around the country. Because of this, electric power system engineers recognized many years ago that optimum system economy could be achieved by producing electricity at each instant of time at the source having the lowest incremental production cost [34].

To determine the minimum incremental production costs, they had to know the incremental heat rates and fuel costs for each of the various generating units. The incremental heat rates told them the energy (measured in BTUs) required to produce each additional kilowatt hour at a particular generation loading point. The fuel costs applied to the incremental heat rate provided the incremental cost or production. This cost, if properly calculated, was the incremental cost to replace the fuel being consumed. Through this technique, electric utilities were able to schedule the production on their various generating units in the most economical manner. Obviously, decisions on which units to operate each day were part of this overall incremental cost dispatch optimization. It was also recognized that the transmission losses associated with various dispatch arrangements could result in differences in costs which had to be included [35].

As a result, dispatch methodologies were developed based on incremental production costs and transmission losses. These methodologies included both off-line calculating methods and on-line direct control procedures. The central dispatch computer in most systems has the necessary cost information and continuously obtains the additional information needed to do the most economical dispatch. It then sends out signals to the various generating units to control them so as to achieve maximum economy.

Pooling and Coordination

A "power pool" is a group of separately-owned electric power systems contractually committed to coordinating the planning and operation of their facilities in a manner that approximates (to varying degrees) a single ownership. In brief, the benefits of power system coordination (power pooling) are [24][36][37][38]:

1. Lower installed reserve requirements - a result of diversity in generator unit outages and in the time peak loads occur
2. Ability to install larger generating units, having a lower cost per kilowatt
3. Lower spinning reserve requirements
4. Ability to interchange economy energy

The penalties may not have been given the same emphasis, but they can exist. They are:

1. Increased transmission requirements
2. Organizational complications
3. Larger areas may be affected by system disaster

Generally, the advantages of pooling far outweigh the penalties. However, as the electrical size of a fully-coordinated system (power pool) increases, the incremental benefits gradually become smaller and the incremental penalties become larger. Consequently, there is an optimum size for a power pool or coordination area [24].

The benefits listed result in cost savings. The first two are primarily capital investment reductions and are the most important. The last two are operating savings and are relatively small in comparison. Reductions in spinning reserve requirements are limited by allowable minimum machine loadings, the need to distribute spinning reserves for transmission protection, and the need for adequate regulating capacity to maintain frequency and interchange schedules. Savings due to economy energy interchanges are in some measure offset by the ability to postpone new efficient generator units because of reduced capacity requirements.

A real power pool, or a fully-coordinated system, is one within which the various areas are completely interconnected and integrated. Transmission within and between the areas is fully adequate to make the savings discussed above. Transmission requirements to accomplish this are provided by the members.

The Use of Transmission to Reduce Generating Capacity Requirements and Fuel Use

The 1964 National Power Survey

In 1964, under the initiative and direction of Joseph C. Swidler, a national power survey was performed. This survey analyzed the long-term needs for assuring reliable and economic electric power supply for the country and looked at alternative technical and institutional solutions. The results emphasized the significant reduction in capital and operating costs that could be achieved through increased interconnections between electric power systems [38].

As a result of the recommendations in this report, the generation reserve requirements among the systems of the United States have been greatly reduced. This was accomplished by significant increases in transmission capacity and interconnections between systems to achieve the many potential benefits of coordination. A recent review of this study, 25 years after it was completed, indicates that almost all of its recommendations were executed on a voluntary and evolutionary basis by the various systems. The additions to transmission, the changes in generation, and the new institutional arrangements required, evolved on a step-by-step basis with timing set by needs and by the availability of appropriate conditions.

The PJM Interconnection

At about the same time, the ability to tie the PJM Interconnection with the systems to the north was being tested through the closing of selected transmission lines as shown in Figure 6 on page 13. These ties were successfully accomplished and began the formation of the transmission grid in the eastern part of the United States. Later, inter-area 500-kV ties were installed from PJM to the systems to the north, the west, and the south.

Savings From Interconnection

Electric utilities in the United States have been coordinating the development and use of their transmission systems and generating capacity for many years. As a result of this coordination, considerable savings have accrued. These savings are the result of:

- Reduced investment in installed generating capacity from:
    - Sharing of installed generation reserves
    - Load diversity and equipment outage diversity
    - Optimum use of available generation sites
    - Use of larger unit sizes
    - Coordination of maintenance schedules
    - Long-term firm capacity purchases

- Reduced operating costs from:
    - Economy energy exchanges
    - Use of regional economic dispatch and unit commitment
    - Optimum use of hydro and pumped-hydro facilities
    - Coordination of maintenance schedules
    - Short-term capacity purchases and sales
    - Reduced spinning reserves

- Reduced transmission investment from:
    - Coordinated regional transmission planning
    - Supply to other systems' loads
    - Back-up to other systems' substations

Estimates show that the ties between regions, coupled with regional coordination procedures, produced annual savings on the order of $15 billion in 1986 and about $20 billion in 1989. These estimates are based on information provided by utilities and operating groups representing a significant portion of the nation and on an independent analysis of available data. About two-thirds of these savings were due to reduced capital investment for generating capacity; the remainder resulted from reduced fuel and operating costs from economy interchange. Other important savings, not included in these figures, were from reductions in spinning reserves and utilities providing transmission service to meet the needs of others. The former resulted in fuel and operating cost reductions; the latter in transmission investment savings.

These figures show the minimum total savings achieved through coordination between companies and systems. Additional major savings resulted from use of the transmission facilities within each region and system that are not included here. Future levels of savings should be much higher as generating capacity surpluses disappear and oil and gas costs increase relative to coal and nuclear energy.

Generating capacity investment savings were a direct result of the availability of transmission, the procedures and arrangements to achieve the necessary coordination, and the realization that each system had to subordinate its own interests from time to time to meet the needs of the pool or region.

Analyses [17]have shown that interconnections have reduced the national requirement for generating capacity about 13% (80,000 MW) in 1986. This represents a capital investment savings of $85 billion at $1,060/kW, the average cost of generating capacity added in 1986, producing an annual savings to the U.S. of about $11 billion, based on fixed charges averaging 13%.

By the mid-1990s, this capacity savings could grow to approximately 120,000 MW with even greater capital investment savings and annualized savings for the customer.

The operating and fuel cost savings from economy interchange vary considerably with the interregional fuel cost differences between oil and gas-fired generation and coal and nuclear generation. If oil and gas prices rebound in the future to their late 1970s levels, these savings will increase significantly.

Nationwide, fuel and operating savings were about $3.5 billion in 1986 and were a result of inter-utility coordination in planning and operations. These savings are directly attributed to the well-developed, reliable transmission systems that interconnected these utilities, and resulted from savings from coordination within a pool or region, and from savings from coordination between pools and regions. The differential between interregional and intra-regional savings varies. For some pools or regions, the savings that resulted from economy interchange within the pool or region were larger than the savings from interchange between regions; for others the reverse was true.

This is not surprising, since the ability to achieve such savings provided part of the impetus for pool and coordinating group formation. On the other hand, interregional savings also played an important role. For example, very significant savings are still being made by the New England Power Pool as a result of transactions with the New York Power Pool, Hydro-Quebec, and New Brunswick. In 1986, these savings from interregional coordination were approximately $19 million versus $16 million for interchanges within the pool.

These operating and fuel cost savings resulted from the cooperation of interconnected companies made possible by interconnecting lines, economy interchange and regional incremental cost dispatch. They were very large when there were significant differences in the costs of fuel for power production in adjacent regions. Typically, these savings have come from the interregional sharing of low-cost hydroelectric, coal, and nuclear resources.

Required Coordination Procedures

Coordination among regional entities is essential to achieve the savings described above. These savings were realized because the utilities were willing to coordinate with each other in many activities such as participating in intercompany and interregional studies. This participation required full disclosure of future needs, potential plans, and capital and operating costs for each system. It also required the contribution of significant personnel to conduct intercompany studies and planning activities. These cooperative efforts were increased over time, as the significant savings became more and more apparent.

The Evolution of Planning and Operating Criteria [39]

Key to successful development of power systems and the coordination of their design was the development of guidelines for the evaluation and assessment of system expansion alternatives. Such guidelines have evolved as system planning and operating criteria.

System Planning

Electric power systems have been planned and developed in an organized manner for more than 60 years. In the initial years, planning involved the informal cooperation of a number of individuals from several different departments. Coordination procedures and policy guidelines evolved gradually. In some cases, however, there was inconsistency between studies and between individuals.

System planning is the preparation of a rational program for the development of a system, so that it can evolve in an orderly and economic manner. It includes forecasting loads, rationalizing ecological and environmental factors, anticipating trends in equipment design, and coordinating the various elements of the system into a well-designed whole. It is particularly concerned with plans for changes and additions to the system. It is concerned with the operation, design, and construction procedures only to the extent necessary to expand the system in an orderly manner.

Briefly, system planning is the process of determining what facilities and systems should be provided and when and where they should be provided, to assure adequate service at minimum average annual cost consistent with maintaining a wholesome environment.

The planning of the equipment and facilities to be installed and the procedures to be used in the operation of a particular system were complex tasks involving many skills, a great deal of data, and organized analytical efforts. The optimum plan for any one system, or portion of a system, could be dependent on or could affect plans for other portions of the system or other systems. In order to plan systems in an orderly manner, policy guidelines were essential.

Planning Criteria

In 1927, the first electric utility system planning department was formally established in the U.S. at the Public Service Electric & Gas Company in New Jersey. During the next 20 years the system planning process continued to evolve. The number of personnel in the planning department continued to increase and the computing devices available improved. In the early 1950s it became evident that written planning criteria were needed to guide the many individuals and activities involved in planning an electric power system. Such written criteria also provided a basis for comparing criteria for one system with those of another to insure that a consistent approach was being used.

I began work in the PSE&G Planning Department, in the distribution planning section where I reviewed requests for specific reinforcements from all of the various field divisions. Policies existed for the relaying and protection of the subtransmission circuits and for reliability, voltage standards, etc., for distribution circuits.

We were fortunate to work for a gentleman by the name of Bob Hooke, who taught us that the way to establish a coherent rational policy for managing this type of operation was to write criteria or standards. These established the policy that was to be used in developing a system. At first these were used for screening requests for funds or system additions. Later on, these were made available to all individuals involved in designing and planning so all could work based on a consistent set of management objectives which we called planning criteria.

These planning criteria were not intended to be arbitrary, rigid rules to which exceptions could not be made. Any engineer had the right, at any time he or she wished, to ask for an exception to the criteria. The key was that individuals could not make exceptions unless they asked top management and presented the specific circumstances showing why either higher or lower standards should be used. It was therefore presumed in managing these operations that all system designs met the specified criteria unless such an exception had been asked for. This considerably reduced the amount of detailed checking that was required in approving plans, requests for appropriations, etc.

Subsequently, I became involved with developing new techniques for reactive planning, and with the design of the transmission network. These techniques involve the revision of criteria and standards used in planning of the transmission system, the analyses of system losses, and, most importantly, with the development of new interconnections and the pooling concept. This work got me heavily involved in generation planning, calculation of production costs, reliability methods, all of which will also be discussed later. Starting in the mid-1950s, the use of digital computers reduced the burden of computation and significantly improved the flexibility for system analysis that was then achievable with network analyzers. This enabled the analysis of design alternatives to optimally meet the planning criteria. The purpose of planning criteria was to define the reliability of service to be provided.

The planning criteria, taken as a whole, provided this definition. They stated broad principles or policies rather than design specifications. Arbitrary or unreasoned application of them was avoided, and modifications were, at times, found to be justified in unusual situations. For example, higher than average reliability of service might be called for in high-density urban areas; and conversely, some scaling down of reliability in areas of very low-load density was sometimes justified for reasons of economy. When more than one criterion covered a given situation, the criterion resulting in the highest reliability of service was applied.

Through the years system planning became an increasingly definitive process; frequently the decision to follow a given course of action was based on a mathematical evaluation of its relative reliability, as well as its relative economy and environmental impact. These methods were utilized in determining some criteria. Others were based on experience: for example, the boundary between acceptable and unacceptable service reliability as evidenced by public or political reaction.

Many of the contingencies specified in criteria occurred very infrequently at the specified load levels and system conditions. However, the facilities installed to meet these criteria provided an overall system capable of meeting the contingencies which did occur in actual operation. Equipment ratings and capabilities required for planning purposes were carefully defined. Nominal and acceptable system operating conditions were also defined. The bases for planning system reserve or spare requirements were delineated taking into consideration equipment maintenance, equipment breakdowns and electricity usage in excess of forecasts.

The specific contingencies which the system was designed to withstand in order to provide adequate service were organized in separate sections corresponding to the various portions of the system. Each section listed the outage contingencies for which provision was made. Each portion of the system was also made adequate for any of the contingencies in any other portions of the system. For example, the transmission system had to be designed to be able to withstand the outages of generators; the distribution system had to be designed to withstand various substation outages, etc.

Growth to Meet Regional Planning and Operating Needs

Because of the interrelationship of reliability problems in one system with the reliability of service rendered in another, NERC was formed. It became evident in the early activities of NERC that systems were being designed to different reliability standards or planning criteria. One system was providing for the occurrence of a three-phase fault plus the improper functioning of a relay or circuit breaker. This system was designed to operate satisfactorily for these contingencies. Other systems, however, were using considerably less stringent criteria. They were designed only to protect against single phase fault and not against more serious faults or failure of circuit-breakers or protective schemes. Interconnection of such systems having important inconsistencies in reliability criteria presented a severe problem. The systems designed to the more stringent standards would have problems caused by adjacent systems which were not planned for such a high degree of reliability. The only solution was to develop planning and operating criteria on a regional basis to which all in the region would subscribe.

This was not an easy task. On a national level, I participated in this work through the EEI System Planning Committee. On a pool level I participated through the PJM Planning and Engineering Committee and later through the Mid-Atlantic Area Council (MAAC) Area Reliability Coordination Committee. We found that the differences in the spending approaches and reliability practices of the managers of individual companies were not easy to resolve. It took a number of years and required a significant effort, but finally criteria were developed for each reliability council. They established a basic core of criteria, or principles, for the U.S. and Canada through the North American Electric Reliability Council which were used by the regional councils to coordinate criteria. These specified the contingencies that were to be provided for, and, generally, the magnitudes of service reductions or interruptions that were acceptable for the various types of contingencies.

However, difficulties still existed. Part of the activity of the North American Electric Reliability Council and its Interregional Review subcommittee, on which I served, was to annually review the reliability conditions in the various systems to see how they affected the reliability of other systems. During these reviews, we found that each of the systems was measuring the power transfer capabilities of the transmission network that connected it to other regions in different ways.

To assess the reliability of a regional system, the needs for interregional transfers and the capability of the system to meet these needs had to be evaluated on a consistent basis. Only if data were developed by the various systems, regions, and reliability councils, could reliability conditions be properly assessed and compared. Ted Nagel, who was chairman of the Interregional Review Subcommittee, appointed an individual to develop a consistent set of criteria and definitions for network transfer capability. After one year, because of the wide differences of opinion around the country, practically no progress was made. Ted then asked me to take over this activity. Through a series of meetings throughout the country, we finally arrived at a set of criteria which, though far less than perfect, was accepted as minimum national standards. These covered two types of transfer capabilities: Interregional Transfer Capability and Transregional Transfer Capability. The Interregional Transfer Capability specified how the capability to transfer power between adjacent regional systems was to be measured. The Transregional Transfer Capability specified the need for and measurement of the capability for transfers across systems. In order to develop these criteria, many compromises were necessary. Only through persistent effort was an agreement finally reached.

In 1973, these definitions were originally approved and published for comment and trial use. Later, the majority of the regions decided to drop the definition for Transregional Transfer Capability. They argued that it was not the requirement of any system to have its system handle any specific or required transregional transfer. In light of developments of the Arab oil embargo and other subsequent large energy transfers across regions, the failure to adopt this definition looms as an important mistake.

The original definitions for the measurement of Interregional Transfer Capability have continued to evolve, and will continue to be modified from time to time. We still lack any agreed-upon criteria for defining or determining the required Interregional Transfer Capability.

In conclusion,[40][41] the key objective of the criteria and methods used in electric power system planning in the U.S. was balance; balance between generation and transmission facilities, balance between capacity and energy considerations, balance between existing and new technology, balance between solutions optimum in one region and those optimum in another, and balance between the needs of the next 5 to 10 years and the longer term future. Because planning is a continuing process, these criteria and methods must continually evolve and planners must recognize that the key to dealing with future uncertainties lays in the increased use of probability techniques.

Sharing Benefits and Allocating Obligations

The Cooperative Approach

Opportunities Taken

During my career with transmission systems, there have been opportunities for significant beneficial changes . One of the most significant was the interconnection of the various regions and the coordination of operation between these regions. These interconnections required a great deal of study and technical analysis to ensure that the resulting larger networks were properly designed and were operable without having major disturbances or cascading outages. The benefits from these interconnections were massive, estimated at about $20 billion a year.

I was personally involved with some of these ties as Chairman of the Coordinated Planning-Engineering Committee of the PJM power pool. This Committee had as members a representative from each of the other PJM companies. In addition, we had representation from other adjacent systems, particularly the Allegheny Power System and the Virginia Electric Power System which was represented by a good friend of mine, Charlie Rudasill. In these activities, it was necessary to ensure that what PJM was doing in tieing to other systems was beneficial to both PJM and those systems. This required cooperative effort and people willing to make compromises in the overall design. If a selfish approach had been taken by some of these individuals and their companies, the massive benefits from inter-area ties would certainly have not occurred in the early 1960s, as they did, and might not have occurred to this date. The willingness to plan and design systems based on the overall regional needs and interests was essential. This was made possible because all agreed that we should develop the most economic system, including generation and transmission, regardless of corporate boundaries and service territories and later on allocate the subsequent costs and benefits.

A key to this allocation of benefits was the development of a methodology for analysis. The basic approach was to look at what each company, system, or pool, would do if it were not part of this coordinated development, to see what their independent costs were and then to determine the total regional costs with independent development versus a fully-coordinated development. This resulted, frequently, in some systems saving considerable amounts of money and other systems having to spend extra money. Procedures were developed for those who saved to pay the extra fixed costs of those who had to spend more, plus an additional amount to give them a fair share of the savings.

In developing the procedures for sharing the costs for the PJM 500 kV inter-area ties and the PJM internal 500 kV system, we were asked by Ed Snyder, then Chairman of the PJM Management Committee, to develop a procedure and a proposal for sharing of such costs and to illustrate the benefits to each of the companies. The PJM chief executives accepted the proposal with only a few minor changes. I learned from this that if all those participating in a cooperative effort can be shown how and why they benefit, and the magnitude of their benefit, achieving consensus is a relatively easy matter.

I used this philosophy throughout the rest of my career in interconnection and intercompany negotiations. The only way that any joint, coordinated effort will go forward is if all of the participants are winners. I believe, today, there are additional opportunities for this approach; however the increased emphasis on market-based, competitive arrangements makes the use of this approach much more difficult and far less likely in the future. The economic penalty from abandoning this approach is going to be, in my belief, very severe to the American public.

An Opportunity Lost

When I was Chairman of the EEI System Planning Committee, a number of us proposed that the utilities study not only the development of additional interconnections between the pools and regions, but also the provision of transregional transmission capacity. This is transmission capacity across a region entering one side and going out on the other. This concept was also discussed at NERC meetings. Out of this, in 1970 a proposal was made to set up a special group to look at the possibility of transmitting low-cost coal energy from Kentucky and Ohio across PJM into the New York/New England area. This study was called the PONY study for Pennsylvania/Ohio/New York and was initiated in 1971 and completed within six months. It demonstrated significant potential savings from building 765-kV transmission from Ohio into the New York area.

A meeting was held in Philadelphia including representatives from Consolidated Edison, Niagara-Mohawk, the PJM companies, AEP and Allegheny Power System. The large anticipated savings were reviewed and mechanisms for achieving the benefits were proposed. The majority of those present were in favor of proceeding with the acquisition of the necessary right-of-way and further detailed studies. The principle opposition, however, came from Consolidated Edison and the Niagara-Mohawk Company. These two companies would have benefitted most from the delivery of this low-cost power. Their representatives indicated their companies would not participate in the arrangement if they had to provide any capital funds for the project. The remaining companies were unwilling to provide the bulk of the capital needed. As a result, the proposed project was abandoned.

In my view, the failure to organize the necessary support for this project resulted in a great loss to the United States. During the transmission oil embargo in 1973, and since that time, the limitations in the existing transmission system have prevented the delivery of coal-generated electricity to displace oil in the east; our nation has paid a massive economic penalty in terms of extra fuel costs. This penalty has continued to the present when the ability of the companies in eastern PJM and New York to import power from the west has been impeded by the lack of this 765-kV transmission system. The ability of New York City and Consolidated Edison to import power from Canada has also been reduced. There is no question in my mind that the failure to build this 765-kV system from Ohio into the New Jersey/New York/New England area was an enormous mistake. Now the construction of such system is far more difficult and costly and, many believe, impossible. A lesson for the future lies in this experience.

These examples illustrate the advantages of voluntarily reaching agreement on sharing the benefits of regional pooling. To achieve this, new procedures were needed to allocate fairly the benefits of this coordinated use of transmission systems so each transaction would benefit all participants.

Criteria for Allocation of Generating Capacity Savings from Interconnections

The participants in a pool or coordination group are entitled to receive a share of the total generating capacity savings which their cooperation helps produce. A "win-win" condition must be established, or participation of all cannot be achieved. This sharing in the economic benefits is the key motivating factor in fostering cooperation. The following are criteria and methods developed for sharing the benefits of coordination:

1. *Fair Allocation of Capacity Savings from Pooling and Coordination*

A key question in any pool analysis is how the capacity requirements and the consequent savings from pooling should be distributed among the individual members. The key factors to be considered are:

- Contributions to savings made by each pool member
- Equitable distribution of benefits to consumers by each of the pool members

2. *Provision of Incentives for the Most Economic Plans*

The allocation methods selected should give the maximum incentive to each of the pool members to minimize the overall long-range costs for the pool by ensuring:

- The installation of generating units of the optimum size, type, and location
- That the capacity needed to provide adequate reliability will be planned for
- That the building of excess generating capacity will not be encouraged or rewarded

3. Recognition of Past Procedures and Agreements

Because much of the generation currently in place was installed under existing power pool procedures, unfair penalties should not occur retroactively due to changes in procedures. New procedures generally require some "phase-in" period.

4. Discouragement of "Sharp Shooting" Practices

It is essential that the methods used not encourage "sharp shooting" practices, such as tailoring estimates and future projections to reduce obligations or increase profits. These practices are merely attempts to "beat the system," not to provide more economic or reliable service.

5. Relative Stability of Capacity Margin Requirements

It is not feasible to plan an electric power system when large changes in its reserve requirements occur frequently. Methods providing gradual evolutionary changes in obligations need to be selected, since they are far easier to apply.

6. Ease of Calculation and Understanding

Capacity allocation methods that are relatively easy to calculate are desirable. Such methods are easier for regulatory and corporate officials to comprehend. They also make it possible to check calculations by individual systems, if needed, and make it easier to understand the key factors affecting individual systems' capacity obligations.

Methods of Allocating Capacity Savings and Determining Capacity Requirements [17]

The savings in generation capacity resulting from the interconnections between systems are usually very large. A key question is how the capacity obligations should be allocated to distribute the savings fairly among the individual systems. In my work, I used a number of methods for allocating such savings. Among these were:

- Equal Capacity Margin
- Dowry
- Equal frequency of dependence

- Average capacity on forced outage
- Largest unit/plant

Underlying each of these methods was the use of the same one-day-in-ten-years loss of load probability (LOLP) criteria for the pool as a whole.

The capacity requirements were adjusted to achieve the overall pool requirement, since the individual requirements will generally not add to the total pool requirement with any of the above methods.

The impact on individual system capacity requirements from each of these methods is shown for an actual system in Table 5. There were significant differences in the capacity requirements determined by the various methods.

The equal capacity margin method was the simplest to understand and determine. Each member has the same percentage requirement as the pool requirement. With a pool reserve requirement of 19%, all members have exactly the same percentage requirements. This reduced any rivalry that existed between the systems by giving them all the same percent requirement. It also eliminated some of the "sharp shooting" that can come from the other methods. Using equal margins encouraged the power pool members to work as a group to provide the most economic service in the future.

The dowry method assigned capacity requirements to an individual member in such a way that by that member's joining the pool, no harm would be done to the other members of the pool. In this way each member must have enough generating capacity to prevent lowering the reliability of the remaining members of the pool. The dowry method essentially assigns all the incremental benefits of increasing the pool size to the individual member that is visualized as joining. None of the benefits in this method go to the remaining members. For these reasons it should generally not be used to assign capacity requirements. It can be used, however, to establish the maximum benefit any system should receive.

The equal frequency of dependence method set each member's capacity requirements based on how often they would need assistance from their neighbors. These capacity margins resulted in each of the members

TABLE 5

Individual System Capacity Requirements in Percent Capacity Margin for Various Allocation Methods

(Listed in order from largest to smallest system.)

METHOD	System											Total
	A	B	C	D	E	F	G	H	I	J	K	Group
Equal Margin	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0	19.0
Dowry	21.7	18.2	17.3	18.0	13.9	9.5	14.8	10.7	13.8	26.1	26.0	19.0
Equal Freq. of Dependence	14.4	9.5	13.4	20.6	23.1	9.1	30.3	17.2	63.5	23.0	9.3	19.0
Avg. Capacity on Forced Outage	20.1	15.5	18.0	19.9	14.7	14.2	19.3	14.5	20.0	30.7	23.4	19.0
Largest Unit	10.4	7.9	13.8	30.9	20.8	18.6	30.9	31.0	60.4	9.1	8.2	19.0

depending on their neighbors equally often. (The magnitude and duration of this dependence would vary with the size of the individual system, but the frequency of occurrence would be the same.) This level of dependence resulted from an overall pool Loss of Load Probability of one-day-in-ten-years.

The average capacity on forced outage method set capacity requirements based on predicted average annual forced outages for individual units. These were then adjusted to obtain the required overall pool capacity margin. These predicted margins were often quite different from actual experience. The simplistic calculation gave equal importance to peaking capacity with high forced outage rates and base-load capacity with low forced outage rates. For this reason, and the failure to recognize the effects of larger unit sizes, this approach was not generally recommended. Reviews of both historical and projected average forced outages, however, provide a valuable check of the results of various other methods.

The largest unit method is a single contingency approach. If each system had built enough margin to cover the outage of their largest unit, over 14,500 MW of generating capacity (25% capacity margin) would have been installed by the coordination group. This method was undesirable since it would unduly penalize smaller systems when they installed units of a size that would improve overall pool economics.

Measuring Use of Transmission

System Inertia

Electric power systems have a great deal of inertia; they take a long time to change. A power plant, a substation or a transmission line cannot be built easily. The systems we have with us are going to be there a long time. It is important to learn how to make the best possible use of them, whether it is a generating plant or a transmission system. Obtaining the best productivity out of what we've got is essential.

Transmission Functions

The basic functions which transmission performs are sometimes lost sight of, i.e., to provide a means of getting the electric energy from where it is produced to the consumer and connecting our generating plants together, so that they can operate on a coordinated basis, both from the viewpoint of minimizing the total capacity required and using the best or cheapest fuel.

Transmission has one other role which is vital -- it is the key to providing for the many uncertainties we face in the future such as natural disasters like earthquakes, tornadoes, hurricanes, and institutional disrup--tions such as nuclear plant shutdowns and fuel supply disruptions. Without an adequate transmission system these uncertainties are difficult to handle. The overall bulk system reliability depends far more on the transmission system than it does on the generation system.

System Interruptions

Many analyses have been made of the various brownouts and blackouts that we have had in this country. I have never found one that was caused by a shortage of generating capacity. There has always been a shortage in the ability to deliver generating capacity from some other area or some other region. For example, there might have been a shortage in New York with available generating capacity in Oklahoma. I am not suggesting we build a transmission line from Oklahoma to New York, but I think we need to recognize that the lack of deliverability of the energy we generate is the major cause of our reliability problems. We need a balance between our transmission system and our generating capabilities. We must keep in mind that transmission reserves are just as important as generation reserves. We have a number of methods for measuring our generation reserves. Improved methods are being developed to measure our transmission systems reserves.

Studies vs. Actual Conditions

I have found very poor correlation whenever I checked the studies made a number of years in advance against what actually happens in a transmission system. Often a planning study might indicate 400-Mw loading on a line that is really loaded 200 Mw for a specified load level and condition. The actual flow patterns are usually quite different from those predicted by load flow studies. The generation in service is never quite what was used in the study. There are some units out that had not been anticipated; there is always some generator maintenance contrary to the planning assumption that no generator maintenance will occur at heavy load times. The generation dispatch is different than what was assumed in the study; the fuel costs are different; the forced outages are different; the heat rates are different. The peak load that occurs is different from that used in the study. The load distribution is different; growth has come in one area when it had been forecast in another area. And, because of some of our national fuel emergencies, there has been a lot of intercompany, interregional and transregional shipments of power to reduce our oil consumption by using more of our coal resources. All of these factors require some margin for error in planning transmission systems. There is a message here for the transmission system planner or the transmission system designer: the transmission system must provide the flexibility to meet changing conditions.

This check of actual loadings also shows that the utilization of some transmission facilities appears to be low. A review of an entire system and a determination of the ratio of the actual loading versus the maximum capability can be used to calculate a weighted average loading ratio for each circuit or transformer. This shows an average utilization on some transmission systems of 30% to 35%. The reason for this is that, in a transmission system, almost always some weak link, some one circuit, or some one specific region is limited and fully loaded while other lines or system elements have spare capacity. The locations of these overloaded links shift with a lot to factors, sometimes even hourly or daily.

What do these differences between plans and actual conditions mean? One interpretation is that good use is not being made of the transmission investment. It appears to some that facilities are underutilized and the investment is not being used wisely. Another interpretation is that transmission systems really need a lot of spare capacity. This is necessary to take care of the uncertainties of the future and to adjust for the fact that the planned conditions are frequently different from the actual conditions. In my experience the second interpretation has usually been correct.

Use of Dispatch Computers

One way to understand the weak links in a system having a dispatch computer is doing security checks (continuously checking potential contingencies and potential resulting overloads) is to review the record of "hits." These are the specific instances where the computer indicates that if one facility would have been lost, something else would have been overloaded. These are the near-misses. This information can be valuable in helping to understand the system and how it works in real life; not just in the relatively few load flow cases that have been studied. Load flow studies never address all of the situations that really come up on the system -- and many come up that have not been anticipated. A record over a period of time of the "hits" and how they are trending is valuable. If there are a lot of hits, a form of Russian Roulette is being played. The system is getting closer to a disturbance, and someday it will occur. Records of "hits" should be kept for a number of years.

Another statistic worth keeping is the average number of circuits out of service. I know many regions where this average is more than five, and on occasional days as many as 15 circuits can be unavailable. By checking actual "hits," the true capability of the transmission system can be better understood.

Inability to Execute Plans

Another reason for differences between the planning studies and what actually occurs on the system is the inability of the utilities to execute their plans. Generally, the studies were based on certain facilities being in service. As events unfold, a line or a generator unit is delayed. Much of the time this lack of planned facilities may be the result of regulatory proceedings and intervenors. I am sure the public and the commissions do not recognize what these delays, -- these extended regulatory proceedings, -- are doing to the costs the public must bear and the risks that they are causing the public to take.

In other cases, the delay is justified by economic or reliability reviews, or caused by a lack of funds or a change in load forecasts.

Key Factors Limiting Use

For many years I have asked, "Why do we make such low utilization of our transmission facilities?" One very important reason is Kirchhoff's laws. The flows on an electric power system divide in accordance with the laws of science and technology. They divide in proportion to the impedances based on the distribution of sources and loads. There is no regulatory body, no lawyer, no contract, no legal document anyone can write which can cause the electrons, the amperes or the kilowatts to flow in any other pattern than those of the laws of science. This is different than any other delivery or communication system. In my past work with many lawyers I have found that this is a difficult thing for them to grasp; some believe they can draft a contract specifying where the power should flow. The only future possibility is for engineers to develop new technology to override Kirchhoff's laws using some of the concepts covered under Flexible ac Systems on page 98 of this chapter.

A second key factor limiting ac transmission use is that we have load cycles on our systems. The loads are up and down. The loads at 2 o'clock in the morning are not the same as the loads at 2 o'clock in the afternoon. We have different loads on weekends, different loads from year to year. For this reason, the limiting areas in the transmission system shift even hourly.

Our transmission system must also provide redundancy because, unfortunately, the circuits do fail from time to time and must be maintained. More than 15 circuits have been out of service on weekdays in certain regions. We have to provide spare capacity for generation outages and for line outages. Also, we add transmission capacity, as we do generating capacity, in discrete blocks. We might have a transmission shortage in an area of 50 or 100 MW, so we put in a 765-kV line with 3000-MW capacity. Its initial loading of 100 to 200 MW would appear to be poor utilization. On the other hand, such a line can provide most economically for future needs.

Increased use of our existing systems can be best obtained by paying attention to where we have unused capacity existing on the system. These situations occur because a system is a living, growing, changing thing. A system can be planned in 1973 to meet 1980 needs based on transmission reserves being needed in one portion. By 1980, conditions and requirements are different from those planned for. In 1984, a new plant is coming in service and the transmission capacity is needed somewhere else; so, we end up with essentially under-utilized capacities in some areas of the system. The job of the planner is to look at these areas very carefully and see if there are ways in which some of that capacity can be used to help meet future needs. This requires knowledge of the locations of future generating plans and the coordination of generation and transmission planning. The approach for many years has been to design a network arrangement to accomplish this.

Procedures for Monitoring Transmission Utilization

In the past, steps have been suggested for keeping track of our transmission reserves, and the efficiency of utilization of transmission investment. The first thing we learned in all our science and engineering courses is when we want to analyze something, measure it and keep track of it. This approach has been used by some with our transmission systems. Starting in the early 1970s, while at the Public Service Electric and Gas Co., I used a simplistic average transmission loading index as a management tool. Each year a set of system readings was taken under heavy load conditions and an average system utilization index was developed by taking a ratio of loading to capacity for each circuit and calculating a weighted average either based on line lengths or line investment. Trends in utilization were monitored over time. This was done for the whole system and for segments of the system. By tracking these indexes over a period of time and setting a management objective (to improve our utilization over five years from 30% to 35%), improvements were made.

The goal was to improve utilization without degrading service. If reliability criteria were changed, utilization could be improved but service quality lowered. This was not considered to be an improvement in the use of a transmission system.

Maximum Theoretical Transmission System Utilization [42]

In 1987, I was able to interest EPRI in researching methods of measuring transmission utilization. In considering transmission utilization indices, a question immediately arose concerning what constitutes maximum theoretical transmission system utilization. Transmission loadings vary with the hourly, daily, seasonal, and annual changes in system loads. They change as the distribution of the loads throughout the system changes. They also change as generation dispatch schedules change and as equipment is removed, trips out of, or is returned to service. For a reliable system, transmission capacity adequate to meet maximum needs at any time must be provided. This means that transmission capacity will not be fully utilized at other times when loadings are reduced or different.

Because generating and power interchange schedules cannot be followed perfectly as a consequence of practical limitations in power system equipment controls, all systems must provide a certain portion of their generation as regulating capacity to minimize the resultant inadvertent power swings over the transmission system. Even with such measures, it is essential that transmission systems allow some capacity for these regulating swings and inadvertent flows. This reserved transmission capacity cannot be used to supply customer load or to transfer power for others, and will appear to be unused when various types of transmission utilization indices are being computed, even though it is essential for the maintenance of reliability.

Because of the cyclical variation in loads, the need for transmission system redundancy to provide for circuit failures and scheduled outages, the need to provide for limitations in the controllability of generation, and the adherence to transfer schedules, there is a maximum utilization that can be theoretically achieved on transmission systems. The development of transmission utilization indices based on a comparison of actual utilization with maximum theoretical utilization is by far the best way to determine how well the systems are being used. Such an approach would define utilization indices as follows:

$$\frac{\text{Actual loading-to-capacity ratio}}{\text{Maximum theoretical loading-to-capacity ratio}}$$

Factors Limiting Maximum Theoretical Utilization

Research has shown that the maximum theoretical utilization (P) based on system-wide averages over a period of time is limited by:

- System load factors (S).
- The amount of spare transmission capacity or transmission reserves required for reliability for the portion of the transmission network being evaluated (R).

- The amount and location on the system of generation and/or load whose output or consumption conforms to changes in system load levels (N). This factor will also vary for different locations on the system and different time periods.

These factors limit the maximum theoretical utilization for various types of systems.

Annual system load factors (S) for utilities are commonly about 45% to 65%. They are determined by customer loads and are not controlled by the utility. The load factor is the ratio of the average of total customer load to the peak. Load factor is a key variable in determining average transmission system utilization. A system with a high load factor is more likely to have higher transmission system utilization than one with a low load factor.

There is also a need to provide transmission reserves (R) in the various transmission networks. These reserves maintain system reliability during circuit outages for maintenance and for contingencies, such as the sudden loss of generation or transmission facilities, and are different for each network. The amount of transmission reserves required depends on many factors, including:

- The number of circuits in the network
- The distribution of load among them relative to their capacity
- The ratio of their emergency ratings to their normal ratings
- The corrective measures available to quickly reduce loading if contingencies occur

These reserves also allow sales to and purchases from other systems to change with times of the day and seasons of the year, and they provide capacity for parallel-path or loop flows through the system or critical interface (which in some cases are in one direction at one time and in the opposite direction at another). Also, at times, transmission capacity must be left unloaded in order to provide assured transmission capacity to remote generation in case immediate delivery is required. The need for reserves is also affected by the geographic location of generation and load relative to each other, by the levels of imports and exports, and by the operating practices of the utility and its neighbors. It therefore varies over time.

The amount of transmission reserve required also varies from system to system. Those systems with many circuits forming a large compact network generally require less reserve than a system with only a few circuits spread over long distances. Required reserves typically range from 50% in two-circuit networks to as little as 10% in networks with many circuits.

The substations to which electric power is supplied are distributed throughout the transmission network. Individual substations have considerably different load characteristics, depending on the types of consumers they supply. Major industrial plants may operate three shifts a day seven days a week, while other consumers may use large amounts of electricity only a few hours each day in one season of the year. Similarly, the generating plants connected to the network have considerably different operating characteristics, with base load sources operating at full output more than 90% of the time because of their low production costs while others, such as peaking units, operate only a few hours each year. Hydro units may operate at full output 24 hours a day in some seasons of the year and not at all in other seasons. Some recognition must be given to such non- conforming loads and generation -- loads and generation that do not increase and decrease in conformance with system load levels -- and to their location in the transmission network, in determining maximum theoretical transmission utilization.

The degree to which transmission is affected by such non-conforming loads and generation can be included by the factor N. The transmission systems near high load factor loads or near base-load generators have higher maximum theoretical utilization indices than the overall transmission system. Similarly, transmission near low load factor loads or peaking units, or those used that occasionally provide emergency imports for reliability purposes, have a lower maximum theoretical utilization.

Maximum theoretical utilization (P) over a period of time has been defined by the equation $P = S\ (1-R)\ N$, where an estimate of these factors is:

Factor	Typical Value	Typical Range
Annual system load factor	S = 0.50	0.40 - 0.80
Impact of non-conforming load/generation	N = 0.80	0.10 - 2.00
Required transmission reserves	R = 0.25	0.10 - 0.50
Resulting maximum theoretical utilization	P = 0.30	0.10 - 1.00

The resulting maximum theoretical utilization for the typical system is 0.5 x .75 x .80 = 0.30 or 30%.

Methods for determining the factors N and R, as well as the ways in which this method could be applied to key interfaces, are subjects for future research. Certainly, interfaces with only two circuits would need higher reserves (R) than an interface with four circuits. Interfaces that must provide capacity for intercompany purchases and sales during certain periods, or are subject to large variations in loop flow, would also require higher reserves.

It is important to note that this approach appears useful for the analysis of a system or a portion of a system only when a significant period of time or numerous conditions are being evaluated. If only a single hour or a single specific condition is of concern, evaluation of utilization is best achieved by a review of the specific data for the conditions.

New Tools and Methods

The Development of New Computational Tools

Through the years, computational tools evolved and changed. A number of tools used originally are described below so the reader can see the changes that took place. I believe that some of the older techniques that ceased to be used may be of value in combination with future methods that are yet to be developed.

Short Cut Methods

In the early days of transmission networks, the principle computational tool available for prediction of flow conditions, ntwork stability, etc. was the network analyzer. Calculations were also often made using short-cut methods. In some cases, data was obtained from the system, and the actual system was used as a computational tool. For example, in the 1920s, system operators recognized that the systems were linear in many respects; therefore it was possible to determine the percentage of the flow on a given line that would flow on other lines, if the line were lost. Data was obtained by taking each line out of service at a light-load time, recording the changes in flows in other lines, and developing these as percentages of the flow on the line that was taken out of service. These "distribution factors" could be used for any other loading condition on the system, because the network was nearly linear in this regard.

Methods such as Thevenin's Theorem, the switch closing artifice, and superposition were used to make possible analysis of the network with various changes and under various conditions without a calculation of the complete network. I found the switch closing artifice, which I first read about in an electronics textbook, a very powerful tool. This could be used quickly to determine the effects of a change in the impedance in a line, removing a line from service, or adding a transmission line.

For an increase in line impedance all one had to do was visualize the increase in impedance in a line as being an impedance which is short circuited by a switch, and then visualize the switch as being opened. For decreases in impedance in a line, one had to visualize the closing of a switch on a portion of the impedance of the line. For installation of a new line, one had to view the line as being in place, an open switch being closed; the incremental effect of the closing of the switch was calculated by the insertion of a voltage in series with the line equal to the voltage across the open switch before it was closed; for a line outage, one could visualize a switch being opened. Because of the high "Q" or X/R ratios of most transmission systems, these calculations could be easily made on a "dc basis" using only reactance and quadrature voltage. Through the use of the switch-closing artifice, a great many changes in the system could be analyzed quickly and simply. This transfer of methods from electronics to electric power demonstrates the need for branches of the electric engineering profession not to become inbred or too specialized.

Through the developing of "driving point" and "transfer impedances," data was also obtained for use for many other purposes. J.B. Ward [43]of

Purdue suggested a type of "equivalent" for large portions of a network, so the calculations for the network could be limited to only the essential circuits with which one was concerned. This ability to develop equivalents (and I found the "Ward equivalent" to be by far the most valuable) considerably enhanced the limited capability of the network analyzers then available. With the other artifices discussed above, reliable predictions of network performance could be obtained without the use of massive network simulation.

Stability calculations were made using the "equal-area" methods, pre-calculated "swing curves," and at times the "final reactance" method which was suggested by Westinghouse engineers. These analyses were made to determine if stability could be a problem and in many cases to eliminate the need for detailed and laborious step-by-step stability calculations. Through the years, the methods for evaluating stability limitations have evolved as shown in Table 6.

It also became evident, by those responsible for system calculations, that data obtained from short-circuit calculations could frequently be used for other purposes. For example, the percentage voltage improvement from the installation of additional capacitors could be determined from the ratio of the MVAR capacitors being added to the MVA short-circuit duty at the point where they were to be installed.

These and many other short-cut methods used by system designers have been forgotten through the years and certainly are an alternate to the solution of complete networks that has come into vogue because of the availability of fast computers and new software. The skill of the person doing the network analysis was enhanced considerably by these short-cut methods. Along with the development of this skill came a better fundamental understanding of how the network operated. Unfortunately, the development of better computational tools, described in the following sections, brought with it the loss of feel for, and comprehension of, the network itself. We have, through the years, substituted speed for brains. We have lost our "surgical skills" and the ability to go into a network and search out only the specific answer needed. These skills have been replaced with the "shotgun" approach of always solving the complete network, i.e., using computers to do our thinking.

TABLE 6
Evolution of Stability Methods

DATE	MILESTONE	NEW TECHNIQUE	ADVANTAGES
1920s	Steady State Stability evaluation	- Equations - Circle diagrams	Provided evaluation methods for determining limits based on "constant voltage behind transient reactance"
1930 to 1985	Transient stability evaluations	1930 - Equal area	Provided a two machine evaluation technique based on "contant voltage behind transient reactance"
		1940 - ac Network Analyzer with step-by-step calculations for each time increment	Provided an evaluation for up to 10 units based on "constant voltage behind transient reactance"
		1950 - Precalculated swing curves 1950 - Critical switching time calculations 1950 - Final reactance methods	Provided generic curves for use in stability evaluations and screening for severity of stability problems
		1970 - Development of system dynamic equivalents	Provided better presentation of the protion of the network no represented in detail in stability studies
		1970 - Development of digital stability programs	Made possible inclusion of regulator effects, saturation effects, negative sequence damping, etc. Also increased number of units that could be studied and considerably reduced the time required for a study
		1970 - Development of digital stability programs capable of analyzing long-time transient swings up to several minutes, including boiler response	Made possible analysis of system behavior on loss of large units for systems having large interties typical of the major interconnected regions in the U.S.
		1970 - Development of transient stability evaluation procedures faster than real time	Made possible evaluation and control of system during the disturbance to prevent potential instability
		1960 to 1985 - Improvements in digital evaluation techniques	Made possible faster and better solutions
1940 to 1985	Dynamic stability evaluations	- Regulator action and other controls included in evaluation techniques	Provided advanced methods for inclusion of all effects

Network Analyzers

dc Network Analyzers

Network analyzers are analog computers that model the electric power system. They first came into use in the 1920s. I worked on one of the earliest models which was installed in the Public Service Electric & Gas system in 1928. It was a dc network analyzer and it consisted of a dc voltage source and adjustable rheostats which could be connected in various ways to form the impedances and the loads of the network. The dc network analyzer was generally utilized by representing MVA or megawatts by a dc current; the impedance or reactance of the lines were represented by resistance; adjustable resistances connected to the voltage source would represent generators; and resistances connected to ground at various points in the network were adjusted to give the proper loads, either megawatts or MVA, depending on the study.

An important key to the use of the dc network analyzers was the use of superposition. After a particular network condition had been balanced and read, changes in the network could be checked on an incremental basis using superposition techniques and the switch closing artifice. For example, if one wanted to check the effect of a loss of a circuit carrying 35 MVA, all loads and sources would be disconnected. Then that circuit would be opened up and a dc source would be connected in series with the last line and adjusted to produce an opposite direction flow of 35 MVA. The distribution of the 35 MVA flow on the various lines was then read. The incremental changes would be added by hand to the original flow conditions to get the flow conditions with the outage. This technique also helped people learn how the network operated.

This dc network analysis technique involved approximation. Since the loads and flows were being represented by MVA or megawatts, impedances were not represented by resistance, inductance, and capacitance but merely by an equivalent resistance for all three. It was found, however, that as long as the X to R ratio of all the circuits in the network was about the same, this was an acceptable technique. The one thing it did not do, however, was give any losses in the network, and these had to be estimated separately based on line loadings.

Voltage conditions at any point in a network were calculated approximately based on the power factors of the various bus loads. The flow of reactive current in the various circuits was estimated and the in-phase voltage drop was calculated using any one of a number of formulas in common use. The accuracy of the procedure could be checked by calculating the voltage drop through two or more alternate paths; if the same voltage drop was not obtained, a revised estimate of the division of reactive flow was made until the same voltage drop was achieved over both paths.

ac Network Analyzers

The concept of the ac network analyzer originated with the General Electric Company in Schenectady. PSE&G was the first utility to order an ac network analyzer which was installed in 1937. Devices which provided both the real and reactive power components were used to simulate generators, line impedances, transformers, and loads. For economy in the size of its components, the network analyzer operated at 400 hz. It was possible to set up an analog representation of a 60 hz ac network of many different voltages using the "per unit" system. This is a system through which the impedances of the network were calculated in a common volt-ampere base ("per unitized") so that transformers did not have to be represented unless their turns ratios were different from the nominal voltage ratios. Devices known as "tap changers" were used for this purpose.

Through the ac network analyzer, it was possible to represent the complete network in miniature for any particular moment in time or condition. Because in the early days many networks were not interconnected, the early network analyzers had sufficient capability to represent the entire system being studied. Later on, as the networks became integrated, the development of equivalents for external systems became essential. Network analyzers were used to look at steady-state conditions at many different load levels, and for many different outages. Through the use of the planning criteria, the capability of the network to provide services reliably was checked.

Stability studies were required to check the ability of the system to withstand sudden perturbations. These transient stability studies were made using the network analyzer to simulate step-by-step system changes, while calculations were made as the study continued to determine the incremental acceleration/deceleration of the various generator rotors during each incremental period of time. This technique was known as "step-by-step" stability calculations. These calculations were generally confined to transient stability periods of less than one second.

While the ac network analyzer emerged as the computer of choice for load flow and stability calculations, the dc network analyzer continued to be used for three-phase short circuit calculations. In cases where single-phase faults were to be studied, the dc network analyzer at PSE&G was used to set up the zero sequence network while the positive sequence network was set up on the ac network analyzers [44]. By getting an equivalent zero sequence impedance at the point of fault from the dc network analyzer, and connecting this impedance under the ac network analyzer, it was possible to do single-phase fault studies quite expeditiously.

Digital Computers

Technical Applications

The first use of digital computers for load flow studies was suggested by Mr. L.A. Dunstan of the Bonneville Power Administration in 1947[45]. While potential for the use of digital computers looked poor, there were some who felt that, as a minimum, one had to investigate the possibilities. In 1949, a small team was established at PSE&G that began to look into the use of digital computers for load flow and short circuit studies. At that time, our company was using an IBM 604 for accounting purposes. The 604 was a computer programmed through a hand-wired control panel and had the capability of doing a small number of mathematical operations. Early studies, using a mathematical technique known as Verzuh's Method, successfully enabled us to analyze networks with up to ten busses and to make short circuit and load flow calculations.

Shortly after that, Glenn Stagg at the American Electric Power Company, and Jim Henderson at the General Electric Company, developed a new program for doing load flow called AGEL, which used the IBM 650 and significantly increased network analysis capability. This program was freely circulated and its use by others grew rapidly. Subsequently, other load flow programs were developed. Those of Northern States Power and the Philadelphia Electric Company were the most popular.

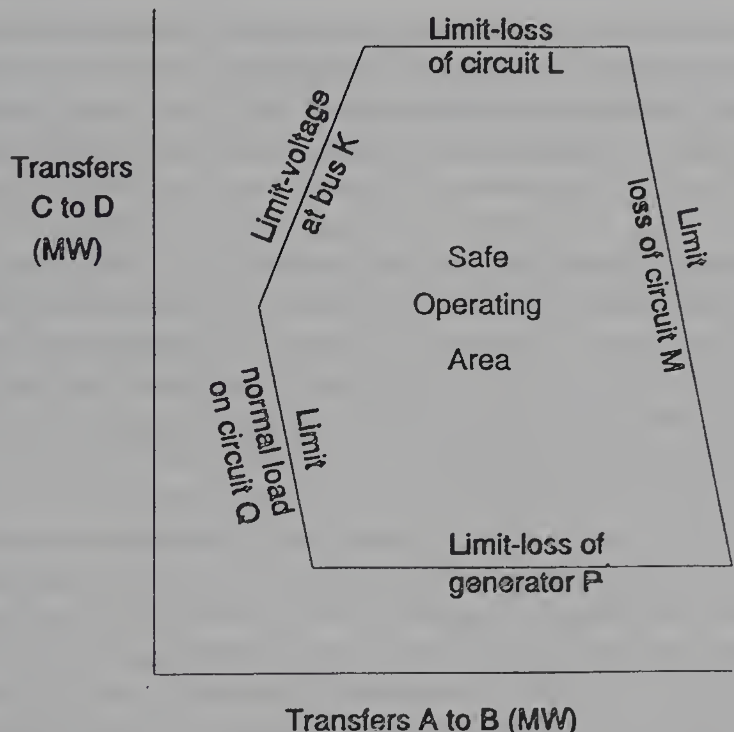


Figure 12. A Typical Envelop Curve To Illustrate Transmission System Limitations

In 1956 the complexity of PJM operations had grown to the point where the PJM manager, Wilmer Kleinbach, needed a study to determine the operating limitations for the PJM pool. This study was conducted on the Franklin Institute network analyzer. During this study, however, it became apparent that load flow runs alone would not be sufficient to provide the information needed for operation day in and day out under the many and varied conditions that the operators faced. For this reason, members of this task force began developing the first "T-LIM" (Transmission Limitations) program. This program, developed mainly by Chuck McArthur of the Pennsylvania Power & Light Company and Jack Zuckernick of GPU, used distribution factor data obtained from network analyzer studies and calculated "envelop curves" (illustrated in Figure 12). These curves showed the boundaries of safe operation for the network, as well as the facility which would be critically loaded and the specific contingency which could cause that loading under various transfer conditions. The availability of these curves in 1956 was a significant extension of the kinds of information that operators had to assist them in their operations.

The first major digital computer studies in which I was involved were made in 1958 and 1959. They dealt with possible EHV connections of the PJM pool to the systems to the north; the New York Power Pool, the systems to the west; AEP and APS systems, and the system to the south; the VEPCO system. These were held at the Corporation for Economic and Industrial Research (CEIR) in Arlington, Virginia. CEIR had an IBM 703 which at that time was the only computer in the United States capable of making calculations for networks of that size. The recent development of new software and small computers has been so rapid that the load flow, stability and short-circuit calculations then performed on the IBM 703 (which required a large room to accommodate all its equipment) can now be performed on desktop machines.

Digital computers and software development provided a tremendous increase in the calculating capability available to those performing network studies. In my opinion, however, this leap forward was not entirely beneficial. It resulted in the substitution of speed of calculation for the brains and analytical skill of the calculator; a decrease in the generation of innovative ideas and methods for the development of the network; and an emphasis on the process of the calculation rather than the functioning of the network. I believe that in some ways, digital computers have been harmful to the development of creative ideas for power system development.

I am also deeply concerned with the emphasis on computer literacy being placed in elementary schools, high schools, and the universities at the expense of mathematical, technical, and economic knowledge as well as the failure to teach young people to understand the fundamental processes and technologies with which they are working. This is a distinct weakness in our education of engineers.

Power Casting

In 1954, the System Planning and Development department was created at PSE&G with vastly increased responsibilities including capital budgeting for the company, digital computer programming for technical studies of the company, and a number of other activities besides generation and transmission planning. This increased responsibility was a sign of confidence from the then head of the electric department, Edwin Snyder. He felt that the planning department had the talent and ability not only to do planning work but to provide many of these integrating services with other departments. It was the System Planning and Development department that became involved in developing a corporate model, accounting procedures, financial analyses, allocation of costs, establishment of rates, and other important aspects of total system management.

During a large part of this time, I worked for Charles Hoffman, and then later, directly for Hollis Sels, the head of the System Planning and Development Department. Both of these gentlemen had creative minds and were very perceptive. As a result, in 1958, the department started a major innovative study with Westinghouse called "Power Casting." The Westinghouse team, headed by Clarence Baldwin, provided the programming; PSE&G and Westinghouse provided system technical and economic knowledge to develop tools for this new age of planning. This was a three-year effort involving approximately 15 people. Out of it came significantly improved computerized reliability programs, improved production costing programs, programs which allowed the study of unit commitment, unit shutdown and unit startup rules, and a great many other tools. Automated transmission planning, sophisticated reliability analyses of transmission systems, the analyses of reactive supply on a probability basis -- all of these areas were probed and new methods developed.

This significant leap forward in knowledge was achieved only because those in authority at PSE&G and Westinghouse were willing to devote enough effort and creative talent to analyze problems and look for vastly improved ways of doing things. These people were also those who would use the tools they developed. This burst of effort and progress laid the groundwork for much of what has been done in the past 35 years in applying probability methods and developing new software for power system analysis.

New Planning and Operating Methods

New Optimization Techniques

With the advent of increased computational capability through larger and faster digital computers, many new approaches for the application of mathematical techniques to the optimization of plans were developed. These included reactive optimization, unit commitment optimization, economic dispatch optimization, etc. Some of these methods were exceedingly valuable. Others, however, involved sophisticated techniques for which adequate data was not available. In order to properly use these sophisticated, new computer techniques, it was essential that users have the necessary skill, experience and judgement to decide whether they were putting garbage in and getting garbage out or whether they were getting a useful result.

All too often the sophisticated techniques have appealed to the regulatory authorities who did not understand the quality of the data and the usefulness of the technique. In their hearings, these regulatory authorities frequently criticized the lack of use of some of these sophisticated new tools, even when it was apparent to experienced engineers that their use would be harmful. The net result is that many of these new tools came into use solely because of pressure from regulatory authorities.

Corporate Models

The need for engineers to present economic and financial data to management when presenting their proposed plans increased throughout my career. Thirty years ago it was acceptable to compare the present worth of costs for alternate plans. As time went on, it became essential that detailed information be obtained so that costs could be allocated between companies and between various functions of the systems. This culminated in the late 1950s when decisions became necessary concerning such questions as ownership versus purchase of a generating capacity and whether to take a 50% interest or a 30% interest in a joint project, etc.

In 1960 I was personally involved in a decision of this type for the construction of the Tocks Island Pumped Hydro project on Kittatinny Mountain where our company (PSE&G) was working jointly with GPU. We each had agreed to take one-half the capacity of the project. There were a number of business alternatives available. We could own all of the project, selling half of the capacity on an annual basis to GPU; we could take a 50 percent ownership; or GPU could own the entire project, with PSE&G buying half the capacity. The question became not only whether the project was justified, but what ownership arrangement was best. As a result of this problem, significant developments were made on methods to determine the impact of these alternatives on the overall company financial picture. How would these decisions affect the annual corporate earnings? How would they affect taxes? How would they affect financial requirements? How would they affect the company's debt rating and cost of money? All of these questions became apparent and were analyzed longhand with many hours of effort.

Hollis Sels - The Creative Manager

Different managers have different styles. All engineers must learn what their managers expect of them without always being given specific instructions, as illustrated by my work for Hollis Sels. Hollis Sels was my superior for almost 20 years. He had started his career with Foresque and Evans. He was one of the originators of "circle diagrams" to analyze long transmission lines. PSE&G decided to embark on installing 220-kV interconnections to other companies and hired Hollis to provide the technical skills needed.

Hollis' personality was quite different from that of Bob Hooke. He was not an organized thinker -- but a rambler. He mulled over problems until he saw the answer. He would wander around the halls, at times failing to return greetings from people passing in the opposite direction, because he was so immersed in thought. He would sometimes come into my office, usually about five minutes before normal quitting time, and start to talk. Sometimes his discussion, which in many cases would appear to some to be rambling, would go on for an hour or an hour and a half. My car pool would leave without me, but I leared that what Hollis wanted was for me to think along with him.

This was Hollis' managerial style. He wanted to talk about problems. He wanted those working for him to ask themselves: "Why did he come in here? Why did he talk about these things? What is he concerned with? How can I help him solve any of these problems?" If one leared to do this with Hollis, one began to find that his rambling discourses were the key to an unusually creative mind. They were part of his thinking out loud, the walking around a problem trying to see how to approach it. He was trying to get others, with whom he worked, to think about the problems also.

Some would consider him a poor manager because he never made direct assignments. I considered him the most creative manager I ever worked for, because he helped me to understand the problems and then left me free to solve them on my own. This managerial style of Hollis Sels has an important advantage over tightly structured task-oriented management because it inspires creativity.

Hollis Sels became convinced that, in addition to the longhand approaches we had used for the Kittatinny Mountain project, we needed to develop computer programs to analyze the effect of our planning decisions on the corporation. This led to the establishment of a departmental project team to develop a corporate model. Bert Blewitt, our engineering economist at PSE&G, was put in charge of this development. The result was a working corporate model for PSE&G which could be used to analyze the effect of alternate plans on many key financial factors. Included were the impact on the need for new financing, on future rates, and on taxes. This corporate model was completed in 1965. I believe this is the first time this was done in the United States.

This tool was used many times for evaluations of decisions by PSE&G. For example, whether to build nuclear or coal plants, or whether to become involved in inter-company projects. Top management viewed this as a very important tool whose development we had pioneered and chose not to discuss publicly any of our accomplishments in this area. The reason was a fear of misuse of the tool. They viewed the regulatory authorities with suspicion. Some of those in regulatory positions had strong political ambitions. Top management believed that making known the availability of this tool and the fact we were using it to make business decisions would soon lead to a request by the regulatory authorities for the results of these studies and for the use of the tool for special investigations by the regulators. This was viewed as a threat to take over the management of the company. I was told to keep the results of corporate model studies in a safe which was available in my office for this purpose. Looking back, I believe this secrecy was a mistake. It would have been better to try to educate the regulators than to conceal information from them.

Reactive Planning [46]

The planning of reactive capacity as a commodity was first undertaken at the PSE&G. This approach was initiated by Hollis Sels and Charles Hoffman. The concept was to analyze the reactive loads and losses on the system and to provide reactive sources equal to the total requirement plus some reserve capacity for contingencies. This concept proved to be very valuable.

Another key to the overall approach was also the establishment of voltage drop limitations on the transmission system for the transfer of reactive capacity. These were used to determine the reactive assistance available from one area to another. This method, along with the concept of "normal switched" and "emergency switched" reactive, was exceedingly valuable. Unfortu-nately, it has been forgotten in the development of some of the recent optimization techniques.

Area Coverage

Area coverage is a characteristic of transmission systems which measures the ease with which transmission can reach potential new substations and loads. The recognition that area coverage was important developed in the 1960s when load growth was still rapid. Those planning the systems began to realize that two alternate plans, which might be quite close in cost, should be compared for their area coverage characteristics. The one which provided new lines over new routes was superior from this view-point. Improved area coverage required the use of additional land and the installation of transmission through new geographic areas . However, it presented significant advantages when one looked at the growing system and its needs in the future. At PSE&G we began to develop area coverage indices for various plans so that we could compare them for this characteristic. We never arrived at a point where we could put a dollar value on the difference in area coverage indices, but it was a factor in making a decision on the final plans.

New Operating Methods

Evaluation of Emergency State Controls

The ability to control a power system during emergencies has always been a prerequisite to adequate reliability. The controls used for this purpose have evolved through the years as shown in Table 7.

Automatic Control of Generation

While generators had been automatically controlled to some degree from the earliest days of the industry by such devices as governors and voltage regulators, the automatic control of generators on a system basis rather than on a local unit basis was a major advance. The first significant efforts were initiated by the desire to consider not only incremental fuel costs in

TABLE 7
Evolution of Emergency State Controls

DATE	MILESTONE	NEW TECHNOLOGY USED	ADVANTAGES
1900	Development of ac circuit breakers		Interrupt overloaded and faulted circuits
1920s	Telemeter loading, voltage and status data to a central location	Telephone pilot wire	Provided system status data for use by operators in making decisions. Operator judgement predominated
1950s	Use of predetermined safe limits and corrective action instructions	Development of stability limits and thermal limit envelope curves	Provided improved technical guidance to operators
1950s	Installation of automatic reclosing on transmission lines	High speed reclosing controls and circuit breakers	Maintain line in service for the vast majority of faults that are temporary
1950 to 1970	Development of tie-line and frequency controls	1950s - Analog computer 1960s - Digital computers	Provided automatic generator response when interchange schedules were not met, when a generator unit was lost, and when frequency declined
1960s	Installation of under frequency relaying	New types of relays developed and installed. Included needed time delays. Also rate of change of frequency relays developed	Provided for designed load reductions during periods of declining frequency to halt the decline
1970s	Automatic service restoration	Use of under frequency relays to restore service when frequency returned to normal	Faster restoration
1960 to 1985	Installation of supervisory controls in dispatch centers	Controls and communications for reliable remote operations	Switching at remote locations can be performed quickly by system operating center. Allowed unattended operation of substations
1960 to 1985	Improved communication to system operating centers	Use of microwave, carrier, and satellites	Better information on present state of system
1927 to 1985	Development of pool dispatch centers	Communications provided with individual company dispatch centers	Provided a mechanism for coordination between company operating centers

determining economic dispatch but also incremental losses on the transmission system involved in the delivery of the power. This led to innovative work by Kirchmayer and Stagg [47][48][49]of General Electric and the American Electric Power Co, Brownlee & Early with their "early bird" computer in the Southern Company [50][51] and also Nathan Cohn of the Leeds & Northrop Corporation [35][52]. These people pioneered the theory and computer devices for evaluating transmission losses in system dispatch. Leeds & Northrop developed an analog computer which provided dispatch signals to all the generators in the system to optimize production costs considering losses. Later on, digital computers were used for the same functions, plus others.

Security Assessment

According to definitions established by NERC, system reliability has two attributes: adequacy and security. Adequacy is concerned with having sufficient generation and transmission resources to meet load requirements recognizing that equipment will be unavailable from time to time. Security is a measure of the ability of a system to withstand various disturbances.

Security assessment has been a requirement of electric system operation since the turn of the century. Table 8 shows a brief evolution of security assessment.

The CEGB Security Assessor

In 1962, The Central Electricity Generating Board (CEGB) installed and operated a security assessor in London for monitoring the security of its transmission system. This was a digitally-driven dc analog computer which had data input to it from the dispatch center. The analog represented the impedances of the transmission network on a simplified dc basis. Through this arrangement, the CEGB was able to look at each single contingency that could occur on the transmission system under the conditions then existing and determine whether there would be any overloads on any circuits for the outage or loss of any circuit. The information to the operators was displayed through a three-light system which I still consider to be as good a man-machine interface as any used anywhere in the world. Each circuit on the mimic display board for the transmission system had a green light, an amber light, and a red light. If a circuit would be loaded less than 75 percent of rating for any single contingency, the green light was lit. If the circuit could be loaded between 75 percent and

TABLE 8
Evolution of Security Assessment

DATE	MILESTONE	NEW TECHNOLOGY USED	ADVANTAGES
1920 to 1960	Develop distribution factors	1920s - Actual readings before and after circuit outages 1930s - dc network analyzers 1940s - ac network analyzers 1960s - Digital computers	Ability to calculate loadings on remaining circuits on loss of a facility at any load level (on-line contingency check)
1950s	Precalculated stability limits	Provided in graphic form	Provided safe precalculated limits to operators
1957	Develop transmission limitations curves for single contingencies	Use of digital computer to develop "envelope curves" for various load flows and intersystem transfers	Provided safe precalculated limits to operators
1962	Use of digital computer to simulate contingencies and identify potential overloads	Analog and digital (CEGB) All digital (PSE&G, PJM)	Fast on-line capability to identify location and magnitude of system risks
1964 to 1985	Use of digital computer to select an optimum solution from available alternatives	Digital calculations using tables of alternatives	Provided advice for consideration by operators
1965 to 1985	Performance of "on-line" load flow	MW only using digital computer; MW and MVAR using digital computers	Provided advice for consideration by operators
1970s to 1980s	Determination of potential severity of various contingencies	Improved computer techniques	Provides better information

100 percent of rating for any single contingency, the amber light was lit. If the circuit had the potential to be overloaded for a contingency, the red light was lit. The operator could thereby scan the board and easily see where his potential transmission problems were located.

I was fortunate to learn about this installation through reading the CEGB Annual Report for 1962. When I went to Europe two years later, I decided to visit them to discuss the overall question of transmission and transmission security. I found my old friends at CEGB, particularly Messrs. Cash and Chorlton, to be valuable sources of ideas. I also found my friends in Electricité de France (EDF), Messrs. Gaussens and Pardigon, who at that time were involved in similar work, very helpful in the exchange of ideas and concepts. This international exchange of ideas and information undoubtedly led to an advancement of the technology and to the development of better security measures for system operations.

U.S. Security Assessment by Computer

As a result of my eye-opening visit to Europe in 1964, I immediately began to advocate the installation of a security assessment computer and dispatch computer by the Public Service Electric and Gas Company and by the PJM. This led to a decision by both Public Service and PJM to install such dispatch computers. These decisions were reached prior to the blackouts of 1965 and 1967, which clearly reinforced the arguments presented in obtaining funding for the installation of these computer systems.

The approach used in the U.S. was different from the CEGB, however, in that we decided on an all-digital approach. The superiority of computers and software available in the U.S. was a key in this decision. Quoting from available records, the security functions that were intended to be performed by these first dispatch computers are outlined below.

a) Continuous monitoring of transmission line and generator MW and MVAR, bus and generator voltages, breaker positions, tap positions, KWh, and frequency

b) Alarming when loadings or voltages are outside prescribed limits, when generators are off incremental loading schedule, or when the status of a circuit-breaker changes

c) Security analysis, consisting of:

(1) Advice to dispatchers of potential overloads that would be caused by a forced outage (generation or transmission) and recommended preventive action.

(2) Advice to dispatchers on how to change generation or re-arrange transmission to relieve potentially overloaded lines.

(3) Advice to dispatchers on the amount of operating and spinning reserve available at any time.

d) Scheduling of future outages, including an evaluation of the effect of the proposed outage on the system in the form of transmission line flows, and lists of overloads both with and without additional contingencies.

e) Voltage control, which consists of advising the dispatcher when voltage is outside prescribed limits and recommending corrective action.

While not all of these security functions were successfully achieved in the initial installations in PJM or PSE&G, the significant advances made by those computer installations have led to the modern EMS systems that exist in the dispatch centers of the utilities today.

Control Areas [21][53][54]

As the individual electric utility systems were being interconnected in the United States, it became quite apparent that new control technologies and procedures had to be developed so that operating decisions and problems in one system did not unnecessarily affect another. This led to the development of what is now known as control areas. A control area is a bounded geographic area within which all generation is controlled by a single dispatch center. All transmission lines entering or leaving this bounded geographic area are metered; and the total flow in or out of the area determined. The control center has a dispatch computer which controls generators to meet optimum economic dispatch and the scheduled amount of power flowing in or out on all of the tie lines.

In addition to the automatic computer control features of the control center, it monitors voltages. There are other manually performed duties such as scheduling of maintenance, handling of emergencies, agreeing on schedules for power interchanges, developing data for incremental cost dispatch, etc. The control area concept has continued to evolve and will grow in the future.

Current and Future Developments

Electromechanical Equivalents

Because of the dynamic characteristics of electric power systems, with disturbances in one location ricocheting through the entire synchronous network, it is highly desirable that each control or dispatch center be able to obtain information concerning the systems external to its control area. Some of this information can be obtained now through communication channels. Efforts through the years have attempted to obtain equivalents for external areas which provide a suitable representation of the external systems to a particular control center. These have to be electromechanical equivalents which satisfactorily represent the external areas [55]. Because these external areas are changing in the specific generation that is on-line (how it is loaded, etc.), these equivalents must be dynamically obtained. A major effort in 1970 to obtain such equivalents culminated in a project sponsored by EEI and later taken on by EPRI. This project had some successes. I was Co-Chairman of the EEI Task Force which pursued this project. Of particular note was the ability to calculate stability phenomena in real time faster than it would occur. This ability theoretically provided the capability to change the system during a disturbance to prevent instability predicted by calculations. This ability to calculate faster than real time has not been pursued since that time, but it appears to be worthy of reconsideration.

On-line Determination of Transmission Use

With increasing concern about the parallel path and loop flows through the various systems caused by other systems, an additional need became apparent. System operators, at any point in time, needed to be able to obtain data for every transmission circuit giving the causes of the loading on the system by various functions. For example,

- own load supplying own generation
- loop flow caused by network characteristics
- parallel path flow caused by transfers between other systems

With such a tool, system operators could more easily determine which changes in the system would be desirable as reliability constraints are approached. They would have the data to see which would involve the greatest cost penalty and make the appropriate changes. Similarly, data would be available for charging for transmission service and losses. Efforts to develop such a tool started with a basic approach using multiple regression techniques but have not yet been fully developed. Recently, the Niagara Mohawk Company announced initiation of procedures to determine transmission circuit use every five minutes on-line during actual operation [56].

Economic Equivalents

The need for and development of electric equivalent circuits has been discussed previously. Almost 30 years ago, it became apparent that economic equivalents for adjacent systems and regions would be very beneficial. These equivalents were intended for use in scheduling generation and economic exchanges of energy between systems. The availability of such equivalents made unnecessary a great deal of data concerning these external systems which could not be easily obtained.

Early attempts to develop such equivalents were based purely on intuitive methods. An equivalent generator that has a capacity availability and an energy cost for peak loads, light loads and intermediate loads was hypothesized for each season of the year. The capacity available and the energy cost was estimated and then compared with production cost studies for the complete detailed representation of the system being analyzed. When necessary, changes were made in the economic equivalents to achieve satisfactory results.

This approach was used in a number of studies. Checks of actual system-operating results with those predicted in studies a number of years earlier have shown a remarkable consistency. The procedure is not a scientific one, however, depending in large measure on the judgement of the individual developing the equivalent. The future should bring better methods for developing such economic equivalents.

New Power System Arrangements

Jointly-Owned Plants

A significant change which substantially affected electric power development was the concept of jointly-owned generating plants. As the most economic unit sizes grew larger, it became more difficult for a single company to justify the increment of capacity that would be added, or to provide the capital investment which would be required for one such large plant. As a result, the utilities began to band together in small groups of two or more to jointly own power plants as "tenants in common." This joint ownership development resulted in the plants being located outside of the geographic territory supplied by some of the owners. Joint ownership made possible the development of large, efficient, low-cost plants. It also resulted in the need to add significantly to the transmission system to deliver the power from more remote locations to the owners of the various portions of the plant.

Overcoming Transmission System Limitations

Electric transmission system capabilities can be limited by a number of causes:

- Thermal loading limits on the lines or equipment
- Stability; both short-term (transient) or long-term (dynamic)
- Voltage limitations and reactive supply

Through the years, power system engineers have developed techniques to overcome limitations from these causes. In order to achieve a clear understanding of the role and economics of the various devices to improve transmission capability, their function must be carefully identified and understood. This makes possible the economic evaluations and cost analyses required.

Thermal Limits

For the majority of the systems in the U.S., thermal conditions, i.e., heating of conductors and equipment, were and are limiting. In these cases, it was usually thermal conditions on only a few circuits in the network that limited the capability of the entire network. Very rarely would an overload exist with all circuits available. Thermal-loading problems usually occurred only when a circuit tripped out or was taken out for maintenance, and only for a few key circuit outages. In these kinds of situations, the important ratio to look at is the ratio of the circuit emergency capability or emergency rating to the circuit normal rating. The more this ratio could be increased, the more the use of a transmission system could be improved. One way to do this was to lower the normal rating in order to raise the emergency rating, since the emergency rating is dependent on the temperature of the conductor (of the overhead circuit or the cable) before the emergency. By lowering the normal rating and raising the emergency rating, transfer capability could sometimes be improved for the network.

Another way was to increase the short-time rating capability of these circuits. Since all thermal ratings are time dependent, one way to increase the short-time rating was to reduce the duration of the emergency. By developing faster corrective actions, higher ratings could be used, and the network capacity increased. Last, but not least, was improving the distribution of power flow over the circuits in the network to reduce the criticality of the loading on any one circuit.

Stability Limits

Stability limits have been improved by the development of the following techniques:

- Fast valving very quickly reduces steam supply to a turbine so that the generator unit will not accelerate out of synchronism.
- Dynamic braking quickly switches in a large resistor to absorb energy and avoid generator acceleration.
- Series capacitors reduce system reactance.
- Faster circuit breakers more quickly remove faults from the system.

Voltage Conditions and Reactive Supply

Reactive sources are needed to maintain proper voltages on a transmission system at various load levels and conditions. There are many types of reactive sources. There are fixed capacitors which are continually connected to the system. Most systems can use a certain amount of these. There were also variable or switched reactive sources, such as synchronous condensers, generators, static compensators, and capacitors that are switched off and on as needed. For these variable sources, three classifications are made in assessing their use to improve the utilization of the transmission system. In designing control logic and developing reactive plans, a good system designer would break them down into these categories:

- Normal switched - These are capacitors or reactive sources that are varied or switched in accordance with the normal load cycles. They are off at light load times and on at heavy load and not energized on weekends or on holidays. They are controlled to come in and out of service with the tide of the loads.
- Emergency switched - These are capacitors which are needed only for some emergency or outage situations. They are used to maintain voltage in situations such as loss of a large generator unit, a transmission line or a substation transformer. They are not in operation all the time.
- Power transfer support - These capacitors support power transfers to other systems.

Their identification provides a mechanism for charging other systems appropriately.

Flexible Transmission Systems

Control of ac Transmission Loading

Many years ago, it was recognized that techniques for improving the efficiency of use of transmission system investment required the use of devices for controlling the division of the flow of power in an ac network that would supersede Kirchhoff's Laws [57][58]. One system for controlling flow in ac networks is automatic tie-line control. This involves the selection of a closed boundary around a geographic area and setting generation controls to maintain a predetermined total flow on the group of lines crossing this boundary based on system requirements. We cannot, however, control the division of load between the lines crossing the boundary.

The following are means for controlling the loading on individual lines:

Redispatch of Generation

Since I have been in the utility business, the one procedure that people have used, when they have a particular outage, is to back off on one generator or one plant and pick up on another, thereby relieving the critical circuit or circuits in the network.

Network Rearrangement

Another is to rearrange the network physically. Open a circuit breaker, or close a circuit breaker. If you have a "breaker and a half" bus arrangement with four lines in it, you can put two on one side, two on the other, and split the bus. This will introduce an extra node in the network that can change flows. Some of these network rearrangements can be made under normal conditions at various load levels, with one arrangement in use at heavy load and another at light load. Others would be done only in an emergency. The concept of changing a network around and not letting it sit there the same year-round has often been forgotten and is worth further review. It will be of value on some systems.

Phase-Angle Regulators

The introduction of phase-angle regulators can help control the division of flow on lines. They have been used in the U.S. since the early 1930s. But angle-regulators (sometimes called quadrature boosters or phase shifting transformers) are large, heavy devices. They are expensive; they have lots of physical inertia; they are slow moving and have reliability problems at the higher voltages. However, they are continuing to be added around the country, particularly where there are problems with circulating currents resulting from loop flows or parallel path flows.

Another device that has been put in to control loading in a specific circuit is "back-to-back dc." This can be installed in an ac network if its cost can be justified by a sufficient improvement in the use of the existing facilities.

Changing Line Impedances

Through use of controllable series capacitors and, in some cases, series reactors, line impedances can be changed, improving the division of flow in the network.

The recent availability of fast, solid-state devices for use with the above techniques offers new potential. These new devices offer the possibility of much faster response. I believe that, in the next ten to twenty years, we are going to see more and more applications of solid-state devices in our electric power systems for improving the use of these systems. These will be load-carrying devices which will act as valves to control the flow on specific circuits in the system.

Static var compensators are an example. Another device, which I have patented, I call a "power injector." [59] This is a static device for injecting a quadrature voltage in a transmission line to raise or lower its flow. It is particularly useful where you need small angles. Its cost could be considerably lower than a back-to-back dc for the same purpose. Others are also working on similar solid-state phase shifters.

Use of Controls and Computers

Computers in operation have been valuable in helping to get more out of a system. One of the things they can do in the future is adjust thermal ratings "on-line." By checking the ambient temperature and the previous loading, a computer can calculate the thermal ratings for various future time periods for a circuit, recognizing what is going on rather than using a rating determined six months in advance. Digital relays can also be programmed to change their settings as conditions change.

A good example of the need for this approach is the French blackout of 1978 [60][61]. A contributory cause of that blackout was the relay settings in use. Relays were set to trip transmission circuits if the circuit loading exceeded a certain level for a certain period of time. The relay settings had been calculated based on the thermal capability of the circuits at 15 degrees Centigrade. On the day of the blackout, the temperature was 0 degrees Centigrade, and thermal capability was much higher than the basis for the relay settings. As a result, relays were tripping out circuits to protect them from overheating before they needed to be tripped. The concept of having computers to adjust relay settings can be valuable. This capability can also be used to make the relay settings more conservative when an unusual operating situation exists.

Chapter 4
THE EVOLVING ORGANIZATIONS

In my work on transmission systems I have often questioned, "What is the best size system?" I have concluded that it must be large enough to have the technical, human, and financial resources to do a good job. It also must be small enough to retain pride of ownership as a motivating force.

These requirements seem essential for all organizations including electric power systems, professional societies, research organizations, and regulatory agencies. When a bureaucracy becomes so large that the roles of the individuals in it are lost sight of, it is no longer the optimum size.

The 1960s brought tremendous economic growth and technological advances which produced a growing need for electric power. To keep up with these demands, the responsibility of the Planning Department at PSE&G grew rapidly. In the early 1960s, additional help was needed and I was told that I could name anyone I wanted to be transferred to the department. To the surprise of my superiors, I named Steve Mallard, who at that time was in a lower level job in a field location. Steve joined us shortly afterward and became my assistant in a few years. He remained my assistant for about fifteen years. I relied on Steve to carry out many key assignments, both technical and administrative. His competence allowed me to become involved in many innovations.

In 1968, I became manager of the System Planning and Development Department. There were more than 100 people in the department with duties including load forecasting, generation, transmission and distribution planning, capital budgeting, expenditure control, intercompany contract negotiations, computer programming, and economic methodology. I again learned the value of good people.

In 1971, on strong recommendation from the planning department and others in the company, PSE&G decided to set up a research and development department. Company management believed in the need for research to develop technologies to meet future needs and requirements. This department was established with Ray Huse as manager, and put under my direction. I was subsequently promoted to Vice President of Planning and Research. Initially, the area of responsibility was solely the electric system. We established an organized procedure for determining our research needs, allocating our resources and controlling expenditures. This was accomplished by establishing research budgeting procedures under which alternatives could be proposed by various departments in the company and reviewed, analyzed, and funded. A $70 million budget was established with projects going forward for a period of a few years.

My responsibilities at PSE&G continued to grow and as Vice President of Planning and Research, the responsibilities for gas planning and gas research were added. Later, the company's testing laboratory was put under my umbrella of responsibility. This resulted in my being responsible for management of an organization of approximately 350 people. This group included many talented people, half a dozen with Ph.Ds in various technologies, most in engineering but also a few in other disciplines. More than 50 people had master's degrees and a large number were skilled engineers and technical staff people. The talents available included those of mathematicians, social scientists, demographers, economists, statisticians, as well as engineers. There is no question in my mind that a great deal of what I accomplished, in fact, the vast majority of it, could not have been accomplished without this skilled array of talent.

I learned that picking good people for difficult assignments is an important skill. The ability to assess how people will do in various types of work leads to the development of a good organization. This ability to pick people, to assess people, is one that is not learned from textbooks. It is partly intuitive, partly analytical. It includes understanding what motivates people, seeing the kind of discipline people have and will bring to assignments, understanding the willingness of individuals to sacrifice for the sake of the group, and feeling the positive orientation of the individuals. Most importantly, I looked for people who didn't complain about roadblocks and problems, but who solved them or looked for ways to solve them. These were individuals with a confident positive approach, a "can do" approach, not individuals who would burden higher level officials with explanations as to why it wasn't done.

Skills Required of Engineers

My experience is that good, determined, optimistic people can achieve almost anything. The resources they are given to do this will affect the quality of the solution; but good people can get solutions to problems even with minimal resources. An "80 percent" solution available when needed is better than a "100 percent" solution that is too late to be used.

It is also essential that engineers be able to communicate well, both verbally and in writing. They need to understand the differences in communicating styles required with different audiences. Communication with the general public must be quite different than communication with a board of directors.

In the regulatory area, the role of engineers has changed considerably. When electric systems were originally developed, and perhaps through the 1960s, the engineers who designed the systems were the ones who were most aware of their costs, their economies, their losses, etc. and therefore were the principal designers of the methods for pricing electricity, both for sales to customers and for purchase and sale between utilities. These engineers were also responsible for intercompany negotiations in connection with joint planning and operating. They were responsible for justifying both plans and cost allocation methods with the various regulatory authorities.

Unfortunately, with the decline of power system education in our universities, the number of individuals with outstanding qualifications coming into the power area declined significantly. The economics departments in the various universities, however, recognized a large void and started to turn out a large number of graduates with economics degrees who obtained jobs concerned with power system costs. As a result, a large part of this work, particularly in the rate and regulatory area, has been taken over by economists. In recent years a general view is being adopted in the regulatory arena that if one is not an economist, one is not qualified to discuss power system economics. I have tried to fight this at every turn. The engineering profession must change this situation since the engineers are the only ones with a full understanding of electric power system costs.

Changes in the Electric Power Industry Organizations

For many years, I was very active in the Pennsylvania-New Jersey-Maryland (PJM) Interconnection, serving in a sequence of various assignments, including Chairman of the Operating Limitations Study Group, Chairman of the Capacity Planning Subcommittee, Chairman of the Coordinated Planning and Engineering Task Force, and member of the Planning and Engineering Committee. Later I became chairman of the Mid-Atlantic Area Coordination (MAAC) Committee. During this period, I saw PJM evolve, reliability councils come into being, and many other events unfold. I also served on various Edison Electric Institute (EEI) committees, various IEEE committees and became very active in CIGRE and the World Energy Council. My purpose in mentioning them at this time is to highlight the fact that it was through many of these personal contacts that I was able to learn and understand what was going on throughout the electric power industry -- both nationally and internationally --in terms of problems encountered and solutions available.

It is important to put the different organizations that have played a role in the development of electric power systems and their interrelationships in an overall context. These organizations were important since the success of an engineer's career depends on his ability to have frequent contacts with people from other organizations who are working on similar problems. The engineer also has the responsibility to participate in the activities of these organizations, bringing to them as much as he or she takes from them. Those with which I have been most intimately involved are:

- The Institute of Electrical and Electronics Engineers (IEEE)
- International Conference on Large, High Voltage Electric Systems (CIGRE)
- The Edison Electric Institute (EEI)
- North American Electric Reliability Council (NERC)
- The Electric Power Research Institute (EPRI)
- U.S.- U.S.S.R. Technology Exchange

The IEEE

Since its founding, the IEEE has been an association of individuals that provided a mechanism for the exchange of technical ideas and information. At the start of my career, I found that IEEE papers presented at various meetings and published in various transactions were invaluable in helping me to learn from others involved in electric transmission and electric power system work. Early in my career I decided that it was essential I read IEEE papers extensively. I established a discipline for myself of reading or at least scanning one IEEE paper per day. I met this objective for more than ten years.

The IEEE was, and still is, organized into a number of societies, committees, subcommittees and task forces. The present Power Engineering Society has provided the principle area for my technical activity. The Power Engineering Society has had a System Engineering Committee and a System Planning Subcommittee in which most of the papers related to transmission system and power system technology were published. Under the Power Generation Committee, there was also an Energy Development Subcommittee in which I was active for some time.

In my opinion, the importance of the IEEE role in the U.S. power industry has unfortunately declined over the past 20 years. One of the reasons for this has been the formation and significantly increased activity of the Electric Power Research Institute. EPRI has funded research projects and investigations which have covered many areas using funds provided by the electric utilities. The results of these investigations have been published, in general, in EPRI reports and journals.

For more than ten years, a review of the papers presented at the summer and winter power meetings of the Power Engineering Society has indicated that more than 50% have been authored or co-authored by individuals from outside of the United States. Early in my career, the people who sat on the various IEEE committees and subcommittees were the most informed and knowledgeable individuals in their U.S. organizations. They were aware of the problems their companies faced and the newer methods that were being developed. In recent years, those on IEEE committees have tended to be assigned more for training purposes than for problem-solving purposes. The problem-solving is done more frequently through CIGRE, EPRI, and the North American Electric Reliability Council (NERC).

CIGRE

Perhaps the most important single organization, from my personal viewpoint, has been The International Conference on Large High Electric Systems (CIGRE). I joined CIGRE in 1962 and went to my first meeting in Paris in 1964. On my way to the meeting I visited the Central Electricity Generating Board in London and became intrigued with the security assessor they had installed in their dispatch center as well as many other of their practices. I spent two days in London visiting with them, and I came away filled with innovative ideas. Subsequently, at the Paris meeting, I sat entranced listening to the papers presented to several thousand power system engineers from all over the world. It dawned on me, at that time, that we in the United States do not have a monopoly on good ideas. I saw others from around the world who were more progressive and more innovative. I learned that good ideas did not necessarily come from advanced nations. In some cases they came from individuals from small, developing nations. Poverty can be a powerful incentive to become inventive.

Through the years I have found that CIGRE has been an outstanding organization through which I was able to exchange ideas with people generally more competent than those I would meet here in the United States, either in EEI, the IEEE, NERC or EPRI. Admittedly, since CIGRE is an organization of nations, the best individuals in these various nations were chosen as representatives. This was not the case for the representatives to the U.S. organizations.

As a result of my CIGRE activities I have maintained contacts though the years with a large group of engineers in various countries whom I consider my friends. Whenever I want to know about approaches used in other nations to solve particular problems, correspondence with these individuals or a telephone call has always resulted in a quick response. When I visit their countries, they are most happy to show me the latest in their facilities and methods. I reciprocated when they come to the United States. These arrangements for international exchange of technology are invalu-able. I also got to know their wives and some of their families, and they got to know mine. I believe that this international friendship and cooperation, with one nation freely helping another, sets an example for government leaders.

The EEI

The Edison Electric Institute (EEI) at one time was exceedingly active in technical matters. The EEI System Planning Committee and the EEI System Control and Protection Subcommittee, both of which I chaired at various times, coordinated the underfrequency load shedding to be used by various regions; compared methods used for load forecasting and their results; assessed the performance of various types of equipment; communicated the innovative, new methods for planning systems; and developed planning criteria. There was about a 10- to 15-year period where the EEI provided, for the investor-owned utilities, a mechanism for individuals and organizations to "let their hair down" on a confidential basis. Since these were closed meetings, if a particular forecasting technique was yielding bad results, it could be discussed. The meeting minutes were relatively superficial and, while papers were presented at the meetings, those published did not reflect the open, full, frank discussion of experience that went on in these meetings. This was invaluable.

The EEI, however, has severely declined in its technical role. EPRI and NERC took over a very significant portion of the work in which EEI had been involved. The principle reason that the EEI has lost its importance in this area is that it represents only the investor-owned portion of the industry. In the early '70s, at about the time that NERC and EPRI were being considered, there was significant discussion of the possibility of opening up the EEI organization to allow the participation of the government-owned utility systems in some manner so it could handle both national reliability and research needs. For a policy change such as this, a unanimous vote was required. The information I have is that one vote at the EEI Executive Committee kept this from happening. As a result, the EEI technical role declined very significantly and EEI has become predominantly a political organization. As one looks back on the history of organizations, one wonders about the individual who prevented the EEI from evolving to fulfill the roles now undertaken separately by NERC and EPRI.

The NERC

NERC was formed about the same time as EPRI to solve the electric power industry's reliability problems. These problems were both institutional and technical. The individuals assigned to NERC committees generally had considerable responsibilities in their organizations and were well qualified for their assignments. The original concept of NERC and the Reliability Councils was to review the plans of the individual systems and regions to ensure that what System A was doing or not doing would not adversely affect the reliability of System B. Within each Reliability Council a review committee was established for this purpose. This also required investigative teams from NERC to visit the regions and review their specific load projections, plans, and reliability conditions.

The original role of NERC, therefore, was to review plans for each region and assess them for the reliability impact on neighboring systems and regions. Through the years this role has changed significantly. The North American Electric Reliability Council has become an organization reviewing, on an overview basis, the national reliability situation. The advent of the fuel crisis and some of the more recent regulatory developments have led to a need for such an organization to review and respond to problems. NERC eagerly and valuably filled this void. As a result, the personnel involved in NERC work have tended to be less system-oriented and more politically-oriented. This again demonstrates the need for developing both institutional and technical solutions in a coordinated manner.

EPRI

EPRI was formed so that necessary technical research too large for any one system to undertake on its own could be performed. As it has evolved, EPRI has become active in many areas other than developing new technology, including:

- Innovative methods of analyses and software including applications of new methods for old and new problems, such as expert systems.
- Investigation of institutional problems such as forecasting electric power needs, pricing for electric power services, and analyzing the socio-economic impacts of power interruptions.

In the technical area, EPRI deals with nuclear power, life extension of existing power plants, new types of energy conversion, energy storage, and many aspects of electric power transmission. The results of this EPRI research are published in technical reports and popularized publications. They receive wide circulation.

I participated in both the formation of EPRI, in the selection of specific research projects for study as a member of its Research Advisory Committee and in the direction of specific research assignments.

A problem with a large organization such as EPRI is the wise allocation of funds. I can cite a specific example in which a decision by EPRI resulted in a delay of more than 15 years in investigations which are now being undertaken. In 1975 I applied for a patent on a device I called the "power injector"[59]. I needed financial support in investigating the applicability of this device and its potential development. The device was an innovative means for using solid state rectifiers and inverters then being developed for use with dc transmission in a device that would inject quadrature voltages in a transmission system and thereby control the flow on individual circuits. I wrote to the Electric Power Research Institute and tried to interest them in this device for more than a year. I was continually told that they could see no importance for such a device. They have completely reversed their thinking and are now embarked on a massive program to develop flexible transmission systems. They are now paying for research and development of such devices. An opportunity for a significant development was lost, perhaps delaying progress by 15 years.

The U.S. - U.S.S.R. Technology Exchange

I have also participated, for the period from 1973-1980, in the US-USSR Technology Exchange Program. I acted as head of the planning representatives in the power dispatching and planning group. I found my Soviet colleagues to be most open and friendly in all but a few areas where they were obviously restricted from commenting on certain matters. I did find, in working with the Soviet engineers, that they were very intrigued with how we did things in the United States, particularly institutionally.

We talked at length about the projection of future loads. In their economy, electric consumption had been projected by a Central Planning Bureau. This national projection was then divided into regions and subregions and so on down until they had the forecasts for each of the various portions of the system and each functional class of load that was essential for designing the system. We, in the United States, however, project loads by forecasting each of the smaller subsystems and accumulating them into much larger systems until we arrive at regional and national totals. Their procedure was top-down; ours was bottom up. After a discussion and comparison of data, they admitted that our procedures were preferable. They came to the conclusion that our system was better because of something we called the "diversity of error." In the U.S. approach, putting together small pieces to get big ones led to some compensating errors. If a geographic district had its energy consumption projected high, another one might be low. When the totals were put together, the cumulative error tended to be less than when it came from a central planning bureau where, if there was an error, it was built into everything throughout the entire system. This concept of "diversity of error" proved to be of interest to them, and I have remembered it ever since. It perhaps is the key to the success of democracy in our society.

The above organizations provided a mechanism for individuals to meet and perform certain assigned roles in a structured environment. They also provide a mechanism for the informal exchange of ideas and information in a great many areas. The discussions at dinner, breakfast, on a bus, etc. provided opportunities which would never occur if the organizations did not exist and did not have meetings periodically. These organizations will continue to evolve and change. It is important that, to whatever extent feasible, their future development be coordinated. There is a certain amount of potential natural synergism between their activities. Every effort needs to be made to take advantage of it. It is important that the individuals in these organizations remain open-minded and be aware of the true problems of the electric power industry.

Our organizations in the United States and in other countries, professional and otherwise, will continue to evolve. Utility systems are merging, others are being privatized, and other significant developments are occurring. The opportunities for making important changes in the future are available.

Chapter 5
THE FUTURE AND WHAT IT HOLDS

The National Picture

The future holds changes. For electric power systems, these changes will be large. They will be both technical and institutional. A key to these changes will be the continuing efforts to establish a reasonable balance between the coordination among utility systems necessary for their economic development and the enhancement of competition between them for the maximum national benefit. The utilities are becoming increasingly competitive with each other and with independent power producers.

We in the U.S. need an improved national energy policy. The role of electric power in this policy is a key one. A "National Power Survey," similar to the one made in 1964, is necessary to determine our future needs and the best technical and institutional ways to meet them.

Technical Changes

Transmission Limits vs. Available Generation

We are now in a period where the ability to interchange power between regions of the country and between individual companies is transmission-limited. This is a result of having more economically justifiable opportunities for power interchange between utility systems than transmission capacity to achieve these interchanges. Generating capacity reserve margins are presently high because of load growth predictions which turned out to be much too high. As a result, the ability to ship power from one region to another is usually limited by the available transmission capacity rather than by the available generating capacity.

Inter-area ties were originally installed to reduce generating capacity requirements by making generating capacity available to other areas for emergency purposes. This was done by taking advantage of the considerable diversities in generating unit outages and the diversities in load characteristics between neighboring utilities to share capacity reserves while maintaining adequate reliability. Over time, with the increase in generation reserves in the various regions, the relative importance of this role declined. Almost simultaneously, however, fuel cost differentials increased significantly between regions resulting in increased energy transfers over these same inter-area ties. Such transfers are usually called economy energy transfers. Unfortunately, the transmission lines that were needed for these increased economy energy transfers were not identical to those needed for capacity purposes. The result was that some portions of our transmission networks could not fully accommodate the higher levels of economy energy transfers that became desirable.

During the next seven years, practically no additional base load generation will be added by the utilities in the United States, although load growth will continue. As a result, generation reserve levels will decline, while availability of transmission will remain about the same. The energy vs. capacity pendulum will be swinging back to the point where, by the late 1990s, the key role of inter-area ties will again become to accommodate emergency exchanges of generating capacity necessary to maintain reliability of service.

Increasing Transmission System Complexity

The history of our transmission systems has shown that average line lengths decrease with time and that the networks become more complex. This means that, over time, the number of lines and systems affected by a given power transfer will increase, resulting in greater complexity in both system operation and design.

Because of these trends and increasing complexities, the risks of cascading outages must continue to be carefully evaluated by the utilities and by the reliability councils. It is essential in the future that systems be operated within these reliability constraints. One thing is certain: the future will require more and better trained people to operate our transmission systems. While new technology is needed, it must be accompanied by skilled human resources.

Transmission Technology

In the future, we must recognize the "root functions" of our transmission systems and the "root causes" of transmission limitations. Through such analyses, it is likely that technical solutions will be developed which first improve the utilization of our transmission systems and, second, help solve our institutional problems.

Concerning new technology, dc transmission seems to be an idea whose time has come. Its ability to control flows precisely is a very attractive feature. In fact, this controllability may serve as a technical solution to certain institutional difficulties. For example, parallel path flows with all their political complexities can be avoided by some applications of dc transmission. The development of a dc circuit breaker is well under way and makes many additional dc applications possible.

Another development on the horizon, whose impact on our transmission systems could be far greater than dc transmission, is the ability to control the power flows on ac systems. We would then have the advantages of dc systems without their special difficulties and conversion costs, and we would be able to increase the capability of our ac networks considerably without the need for new lines and rights-of-ways. A major question, of course, is what will such devices cost and how reliable will they be?

Automation of transmission systems operation will continue to be enhanced, making possible both faster and better responses during emergencies. This should help improve the transfer capabilities of our existing systems. I may be getting a bit ahead of the actual development of this technology, but I believe that system operation technology is continuing to evolve with the potential for some very major changes in the future. In the debate over transmission access and deregulation, everyone must be aware that, like the basic usage of transmission systems, the technology is also a moving target. This new technology may make deregulation and expanded transmission access more or less viable, but it is unwise to ignore its effect.

The adoption of a corrective approach, one in which the vastly improved communications of the future and much faster controls will be utilized to operate systems in a corrective instead of a preventive mode, can significantly increase the capacity of our existing networks. Certainly some of the technologies that have been used in the recent Gulf War to have the U.S.'s Patriot Missiles shoot down Iraq's missiles can also be used to take corrective action on our power systems, preventing major disturbances before they occur. In the past, we have operated our power systems to withstand, in general, a single contingency and not have any undesirable reliability consequences. This has meant we have limited the loading in the transmission facilities in advance of the contingency actually occurring, i.e., a preventive approach. A corrective approach would allow greater loading of our transmission systems and this advance reduction in line loadings would not be required.

The use of the corrective approach, coupled with the application of the new flexible and controllable transmission systems (FACTS) technology being developed by EPRI, could lead to a significant increase in our ability to use the existing transmission systems without degradation of reliability. In the past, our ability to use these systems has averaged between 30 and 35 percent of total capability on an annual basis. New technology certainly should make it possible to improve this average utilization of our transmission systems in the future.

Institutional Changes

Proposals for Future Use of Transmission Systems

While the purpose of this book is to discuss history, I would be remiss if I did not discuss how our past history can guide us in our future decisions. In October of 1992, Congress passed legislation establishing new policies for use of our electric power transmission systems. The Federal Energy Regulatory Commission and others will be proposing rules for the future development and use of our transmission systems based on these policies. These rules are being developed mainly by individuals who have no technical experience and are technically unqualified. They are predominantly lawyers and economists. This lack of technical knowledge can lead to proposals which can be very costly to consumers.

The establishment of rules for the future development and use of our transmission systems requires an understanding of how power systems operate; how power systems are dispatched; how costs and reliability are affected; the procedures for planning the system and the kinds of information that is needed to develop a system that is optimum, or near optimum, on a long-term basis. It is vital that those who have the technical competence in these areas stand up in times like these and oppose harmful suggestions. It also makes it incumbent on those having the proper technical and economic background to make positive, constructive suggestions for using competition to improve the performance of those planning, operating and managing our electric power systems.

If one were to trace the history of our transmission systems from the 1920 Superpower Study made by a Congressional Commission[1] through to the present, it would be apparent that transmission facilities were put in service to make a reduction in installed generation capacity requirements while maintaining the same reliability, and also to make additional economy exchanges possible. As the limitations in our transmission systems change from an energy-driven system to a capacity-driven system, the availability of transmission for third party services will decrease. This is a natural result of the need to use transmission to maintain adequate reliability in the various systems. Because of this "swinging pendulum," I offer a word of caution to those who would like to see drastic changes in the way the electric utility industry is organized and operated. If the wrong changes are made, it may not be possible for the electric utility industry to handle the transmission problems of the late 1990s. Since the function of and need for transmission does change with time, it is essential that we do not direct industry structure in such a way that by the time the change is completed, the need for the change has disappeared. In other words, we have moving targets. This requires that any changes that are made in the industry structure are aimed at the targets in their future positions.

Forces for Legislative Regulatory Change

Starting with the environmental crises in the late 1960s, a significant anti-technology movement arose [62]. At the core of this movement were many sincere individuals concerned about the environment. Other pressure groups purporting to represent the public interest have developed.

Joining together, these groups have played an important role in bringing pressure for legislative and regulatory changes affecting our transmission systems. Unfortunately, most of them have little technical knowledge.

Worse yet, they are not even interested in the views of those who plan, design, and operate our electric power systems. A real challenge for the future is to overcome these anti-engineering biases.

I believe the key to progress in regulatory reform is regulatory competence. We need qualified people in regulatory positions -- people who understand how electric power systems work, how they are planned and operated, their economics, their management, their financing, etc. History has shown it will not be possible to obtain such people unless we allow the appointment to key regulatory positions of qualified individuals who have worked with utilities and with electric power systems. The concept that those who have spent their lives working in the utility industry cannot serve in key regulatory positions because they will be biased is untenable. These anti-engineering, anti-utility biases must be removed.

The world is currently undergoing a tidal wave of change. We see it in Russia and in Eastern Europe where entire governments have been overthrown. We see some of this surge for change in the United States. The primary cause of this is the realization by the public that our institutional systems are not working well. People have become more and more unwilling to keep quiet about the imperfections of these systems. They have overcome the fear of speaking out and are doing so. This is the way the democratic process should work. One of the purposes of this book is to provide additional information so that engineers can have the knowledge needed to speak out.

The International Picture

A large number of the transmission developments that have happened in the U.S., and will occur in the future, are also present in many other countries. The electric power industry is undergoing restructuring in the United Kingdom, Western Europe, Eastern Europe, and the developing countries in Africa, South America, Asia, and Australia. A major factor in this international restructuring is the privatization of existing government-operated systems.

Engineering expertise and experience available in the U.S. can be of great help to other countries in developing sound technical and institutional policies and procedures. We also need to recognize that we have much to learn from the experiences in other countries as they try innovative approaches.

Out of this international exchange of knowledge will come the information needed for determination of future U.S. policies.

EPILOGUE

The legislative and regulatory crisis has revealed strong anti-engineering biases in government. Quoting from an article in Newsweek by Norm Augustine, Chief Executive Officer of Martin Marietta Corporation: [63]

> *. . . our profession must accept the risk of participation in any public debate involving technological issues. It would even seem we have an obligation in this regard if we are to fulfill our potential to be among the guardians of the world's highest quality of life.*

In a 1992 speech to the National Academy of Engineering, President Bush's former Chief of Staff, John Sununu, stated:

> *. . . it is now clear to virtually everyone that science and technology, engineering, are all very critical parts of developing policy and implementing policy at the national and international level.*
>
> *. . . I stress this because what I am concerned about is that as a profession, engineers have been negligent in one very significant aspect -- in their direct participation in the policy making, policy-shaping, and policy-implementing process. And yet the fact is, that we have been reluctant to get in and mix it up with the lawyers and others in the process. We have not just the right to do so, we have the responsibility to do so.*
>
> *. . . And so my plea today is that as a profession we understand our obligation. As a profession, we communicate the need*

for that kind of participation. And on top of that to suggest to you that not to be involved is really to miss something that is fun, that is worthwhile, satisfying, gratifying, and back to the original premise, something that is absolutely necessary.

I cannot state our obligations any better than these two quotations do. We must step forward vigorously and aggressively to play the role which our society demands of us. A society in which national policy is based on a lack of understanding of the technology and systems involved can make serious errors involving long-term penalties to all its people. This is what is happening at the present time in the U.S.

During my career I have made hundreds of speeches and presentations. While many of these were technical in nature, those dealing with policy matters were the most important. Through the years I have learned the importance of communication skills to influence the public and business and government officials. Above all, my experience has demonstrated that the engineer working on electric power systems and transmission systems should always be aware of the need:

- To balance technical and institutional factors -- electricity, the economy and the environment must be brought into harmony;
- To strive for long-range, overall system solutions; and
- To think like an oyster -- convert every grain of sand to a pearl!

APPENDIX

Education, Formal and Informal -- The Advantage of Adversity

The Early Years

I was born on January 3, 1924 in my parents' home in Brooklyn, New York. I lived in a wonderful ethnic neighborhood with a mixture of Italians, Jews, and Scandinavians. My mother learned how to bake all sorts of Jewish pastry. Our Jewish neighbors learned how to make lasagna. My parents shopped on weekends in a Norwegian bakery. The father of my best friend was a Finnish sailor. Within a five minutes' walk of where I lived, I could find both a Kosher chicken market, where live chickens were killed under the prescribed tradition, and a public sauna where our Finnish and Norwegian neighbors went for their traditional baths. Everyone in this neighborhood had come to America (or at least their ancestors had come) with the idea of finding a better life.

In elementary school, we all got along. Standards were high and those with exceptional abilities were put in special classes, given special treatment, and were able to take more than one term at a time. Junior high school had similar standards and a talented faculty. Here again, it was possible to "skip a term" by being put in special classes.

When I was lucky enough to be accepted by Stuyvesant High School in New York City at the age of 14, my eyes were opened by the technical opportunities available to me, the competence of the faculty, and the sheer brilliance of those who were in my classes. Stuyvesant High School was then, and probably is today, the outstanding technical high school in the United States. There were split sessions where freshmen and sophomores used the building and facilities from 12:30 in the afternoon until 5:30 at night and juniors and seniors used it from 7 in the morning until noon.

I worked for about six hours a day during my last two years of high school. After attending the morning session, I would get on the subway train and eat my lunch out of a paper bag while traveling to the messenger company where I started work at 12:30 pm. At 6:30 pm, I left my job and went home by subway, arriving at about 7:15. I would eat, relax for a half hour and go to sleep at 8:30 or 9:00 pm. I was in no shape to do any homework at that time. At about 3:30 or 4:00 in the morning, depending on the amount of work I had to do, I would get up, do my homework assignments, have breakfast, and leave for school at about 6:15 am. My father would always get up at 5:00 am and make the oatmeal, and turn up the coal furnace to provide enough heat so that I would be comfortable while I was doing my work.

My work as a messenger, which I started at the age of 15, was intriguing because it brought me in contact with many interesting and famous people in New York. I met Katherine Cornell and Billy Rose. I visited the World's Fair. I went backstage in the Broadway theaters. I visited the major corporate headquarters. I was a trusted messenger who was given considerable responsibilities. At the age of 16, I was made manager of the messenger company office, doubling my salary.

Cooper Union and the Advantage of Adversity

I had to make a decision on my college education. I knew I wanted to be an engineer and the basic question was should I continue on with my office manager job, try to get a better job, or try to go to college full-time on a scholarship. I decided to probe these alternatives simultaneously. Continuing to work as an office manager for the messenger firm, I applied to the Bell Telephone Labs for a full-time job after graduation from high school and also applied to Cooper Union for admission to the School of Engineering. I began to realize that even though the manager's job for the messenger company was remunerative, I should seek experience and knowledge that I could use in a lifetime career. Therefore, I decided that it was either Cooper Union or Bell Telephone Labs. Bell Telephone Labs was the best choice, because of my family's financial situation.

I was very disappointed when they turned me down. This meant that it was all or nothing with Cooper Union. Since then, I have learned, that things that seem to be disappointments can in the long run turn out to be benefits. I will never know how my life would have progressed if Bell Telephone Labs had accepted me. Certainly, I would not have followed the career path that I ultimately did or had the educational opportunities that I have had throughout my life.

After the week-long Cooper Union entrance exam, I waited eagerly until the decision was made. The morning the letter arrived from Cooper Union, I was not home and my mother opened it. When I came home, she was all smiles and threw her arms around me, and said, "You've been accepted at Cooper Union." I knew then that the Bell Telephone Labs decision had really been in my favor.

In September of 1941, I went off for orientation with 100 other eager freshmen to the Green Engineering Camp of the Cooper Union. The three days we spent there getting to know one another, and the faculty, and being told what to expect in the future, were days I will treasure all my life. They were over quickly though, and we were back at school attending lectures. I will never forget sitting at a lecture on the second floor of the Foundation Building and hearing the elevated trains rumbling by while trying to learn physics, mathematics, or literature.

Looking back, this experience convinced me that the quality of education is in no way related to the physical characteristics of the educational buildings, the amenities available, the comfort of the chair, the presence of air conditioning, or any other physical factor. The quality of education depends on the standards of the university, the capabilities of the faculty, the talent of the students, the ability of its leadership to motivate them and -- nothing else. The quality of education depends on people, not on facilities.

I continued to work while at Cooper Union under the National Youth Administration (NYA) Program which had been set up by the Roosevelt administration. I worked in the Cooper Union museum, which is now the Cooper Hewitt Museum of the Smithsonian where I cataloged the hand paintings done by famous artists on the hat box collection and rebound volumes from Peter Cooper's personal library. This chance to look at the personal possessions of Peter Cooper and to work with them, ensuring their proper repair and continued availability for future generations, gave me insights into the great man who founded Cooper Union.

Later on, I switched to the school medical staff where I was responsible for scheduling all medical exams and performing routine parts of the exams, working with the part-time school physician. This activity included taking blood pressures, heights, weights, respiration, etc. I was fortunate to work with a young doctor who recognized my interest in the functioning of the human body and taught me a great deal about health and the factors determining health. I will always remember the night, after examining a student, the doctor said to me, "I don't think he has more than a few months to live. He has a really bad kidney problem." Three months later, that student was dead.

I had assumed that I could get by in Cooper Union with the same level of effort that I had gotten by in Stuyvesant High School. I was wrong. There was a lot more work to be done to meet Cooper Union's standards than could be done in a couple of hours each day. I tried to get by with only a few hours of work each day, but at the end of the first semester, I was somewhat surprised to see that my grades were not up to the standards I had maintained in high school. I was only in the middle of the class and not too far from the line at which Cooper Union traditionally cut individuals.

In December of 1941 we were all shocked, on that long-remembered Sunday, to hear over our radios that the Japanese had bombed Pearl Harbor and that we were at war with Japan. I didn't even know where Pearl Harbor was. The next day, we gathered at Cooper Union and listened to the President address Congress and we knew that our lives were forever changed.

School schedules were changed. There were no summer vacations. We had classes on holidays, and during spring and Christmas recesses. We all dedicated ourselves to speeding up our education so that we could assist in the difficult tasks that our country faced. In 1942, when I turned 18, I had to register for the draft. At that time I decided that I really could be more valuable to the war effort using my scientific and technical skills than as an infantry soldier. I began to look at the military programs which required engineering talent. I discovered the Navy V-7 program for future engineering officers aboard ship. I applied and, after extensive interviews, physical exams, etc., I was accepted. The Navy let me stay at Cooper Union through December of 1943, at which time, they sent me to Cornell.

By that time, I had successfully finished my junior year at Cooper Union. In my sophomore and junior years, my grades improved considerably because I had learned to meet the high standards of Cooper Union while continuing to work for additional money to pay for carfare, lunch, etc. It was during this period, in addition to working in the museum and the medical office, I took on the assignment of locker room maintenance for the physical education courses that were run at a local gym for Cooper Union students. This included putting soap in the showers, making sure towels were available, cleaning up the locker room afterward, and general assistance to the athletic director of physical training. It also gave me a chance to use the gym and its facilities to keep myself in good shape and to develop my physical skills in a number of areas.

The lesson I learned at Cooper Union -- how to do a great many things simultaneously and successfully, was very valuable. It taught me that you do not let things slide. If you don't understand something, puzzle it through so that you will understand it when you need to. The approach that many students have today that "Well, I'll get that later" or "The professor didn't explain it well" just doesn't work. With the schedule I had, if I did not exercise total discipline in keeping up with all my activities, I would have had a disastrously unstable situation.

This difficult schedule taught me invaluable lessons. I feel an important quality, not measured by any of the techniques that we have now -- the ability of an individual to do a number of things at one time. For example, can someone read and listen at the same time? Almost everyone can look and listen or read and smell simultaneously. I believe the human mind, like a computer, has the capability to accept more than one simultaneous input, or simultaneously accept input and deliver output. Some minds have a greater ability to analyze more than one thing at one time than others. We should develop techniques to measure these abilities.

During my lifetime, I believe I have developed superior abilities to follow several things at one time and be thinking about them simultaneously. Occasionally, I know that people I have worked with have thought that I was not paying attention to them because I was looking at something else or reading something else while listening to them. This was not a sign of discourtesy. This was a sign that I had a lot to do and I could do two or three of these things at one time. I believe this ability to do a number of things at one time was not something I was born with. It was forced upon me during my years at Cooper Union. I learned how to think about Maxwell's equations, schedules for medical exams, and work I had to do for the museum simultaneously.

Because I loved athletics, I also participated extensively in intramural activities while at Cooper Union. I played intramural basketball, football, and softball. I was sports editor of the school newspaper for one year and was a member of a fraternity. With this kind of schedule, the ability to do a number of things simultaneously was the only way to survive.

The Navy

Early one cold January morning in 1944, after a fond farewell to my parents, I boarded a train to Ithaca, New York and Cornell. The first day was hectic. . .we were assigned a place to sleep, given a uniform which didn't fit well, and told where to appear the next day to register for classes. On the following morning, I went to Barton Hall at Cornell to the registration desk for electrical engineering seniors. I had my academic records from Cooper Union and gave them to the individual in charge. After looking them over, he said, "We don't believe you can be registered as a senior." After some discussion, they decided that I would have to register as a sophomore because some of the credits on my transcript did not meet Cornell's requirements. For example, in strength of materials, my courses at Cooper Union were three credits, Cornell required four. I did not have a course in freshman shop at Cooper Union. Cornell required this for engineers. Fortunately, a professor named Eric Gross came to my aid, and I was enrolled as a senior.[1]

I was at Cornell for one calendar year in which I completed three semesters. The last semester was required by Cornell so that I could complete three freshman courses that had not been in the Cooper Union curriculum. This also enabled me to take a number of elective courses in mathematics. As a result, I graduated from Cornell with 170 credits, 140 being required for a B.E.E. degree and 120 required for a B.S.E.E. degree.

[1]Vassell, Gregory S. 1991. "Eric T.B. Gross," in Memorial Tributes, Volume 4, pp. 119-123. National Academy Press.

Eric Gross - The Fighter for his Students

Eric Gross was a strong advocate of his students' rights, especially in the face of unreasonable administrative and bureaucratic procedures. This was amply demonstrated by the action he was able to take on my behalf. He was also a demanding teacher. I do not believe he knew the meaning of "inferior performance" nor would he allow it from any of his students. I remember the unfortunates, sometimes myself included, who would incorrectly solve an equation on the blackboard or misplot a phasor diagram. "You dummkof, how could you do that?" Eric would bellow. Some may find this an undiplomatic response for a teacher, but Eric was involved not only professionally with his students but also emotionally -- despondent when students did not grasp what he was trying to teach them, and ecstatically supportive when the "light finally dawned." He knew how to draw the best from his students, accepting nothing less.

I spent only one year under Eric before finishing my studies. Later in life, our paths crossed many times. He never once wavered from his dedication to the education of top quality electric power engineers. I will never forget him and the great good he did me, professionally and personally, nor will I ever forget the standard of excellence he lead me to expect of myself and others.

Compared to the schedule I had at high school and Cooper Union, the Cornell schedule, though very difficult, was almost a vacation. I attended classes, did homework, and occasionally served a watch duty for the U.S. Navy, in which I guarded one of the dormitories to ensure that it was not invaded by any foreigners or aliens from outer space. I enjoyed every minute of it. My grades improved significantly and I graduated first in the 1944 Cornell class in electrical engineering.

Since there was a further two-month delay prior to my assignment to the Reserve Midshipman's School at the U.S. Naval Academy, the Navy transferred me to Princeton . There, I took additional courses in various aspects of advanced marine technology and seamanship, etc. We were also indoctrinated further in drilling, marching in formation, and obeying orders.

I was finally transferred to the U.S. Naval Academy in Annapolis. At Reserve Midshipman School, we served as plebes for one month, as second classmen for another month, as third classmen for the third month, and as upper classmen during the fourth and last month. The stay at the Naval Academy was another part of my life which I will always remember and treasure. I learned about the traditions of this wonderful organization and met an outstanding group of men. I recognized that discipline is essential in any organization. The ability to function as part of a team, for the good of the team, even at large personal sacrifice, was demonstrated by many who attended the Academy before me. It is a lesson that many in our present society need to learn.

In the history of the United States, there have been individuals who have given up their lives for the benefit of others. I think we need more people who are willing to sacrifice their careers, their wealth, and everything they own for the benefit of our society. Without such sacrifices, our culture, our society is not going to succeed. It is doomed to failure.

My education was not yet completed when I received my commission at the Naval Academy with my beaming parents, brother, and sister looking on. I was then given orders to go to Fort Schuyler, a Navy base on the Long Island Sound. Here I practiced more seamanship, more drilling, and general waiting until my next assignment began -- Steam School in Newport, Rhode Island, where I learned how to operate power boilers. The war had ended by this time, so a portion of my boiler operation time consisted of crawling through an opening in the boiler with three or four of my fellow classmates, sitting down with a pad and paper, and playing "battleship."

After two months of generally becoming familiar with the operation of the boilers, I was assigned to the U.S.S. Springfield of the Pacific Fleet. The Springfield was the flagship of "Cruiser Division 7" and was somewhere in the Pacific. I was transferred to San Francisco where for one month I lived in the Hotel St. Francis at the expense of the U.S. Navy (per diem pay was $10 per day, room cost was $7 per day, and the remaining $3 provided my daily meals).

The Springfield was moving around quite rapidly and the Navy tried to find a port where I could meet with the ship. They found a delightful solution. They would send me to Hawaii and let the people in Hawaii figure out how to get me to the Springfield. I arrived as a passenger on an aircraft carrier, and proceeded to my barracks in Ford Island. I lived in Hawaii for two months with no assignments except to appear three times a week at the Administrative Office looking for transportation to get to the U.S.S. Springfield.

The time in San Francisco and Hawaii were exactly what I needed to recuperate from eight years of very strenuous, almost continuous effort. I had brought some of my textbooks with me along with other literature, and began to re-read them, and perhaps for the first time, to really understand them. I also began to read Aristotle, Plato, Shakespeare, Victor Hugo, Voltaire and other writers and philosophers, works that I read in college but rarely had time to appreciate or understand.

During this period I thought a lot about what I wanted to do with my life. I began to recognize that each of us has only one life and need to use it wisely. It is our most precious natural resource. The wise use of one's own life, and the lives of other human beings, is so much more important than the life of the spotted owl or the snail darter, that I cannot comprehend the attention that our society pays to some of these obscure creatures and their welfare. Somehow or other, human lives must rank far ahead of the survival of these other species.

There is something wrong with a society where millions are spent to save the lives of a few whales or a particular type of tree while we have people living in our cities in filth and poverty that cannot be believed unless it is seen. My three months of unofficial leave in the Navy in beautiful surroundings made me begin to think about these questions -- made me aware of my obligations and my objectives.

I finally caught up with the U.S.S. Springfield in Long Beach, California, where I immediately became the Assistant Electrical Officer. I was aboard the U.S.S. Springfield for about six months. The war was over. The typical activity was to go to sea to practice gunnery, come into port and unload ammunition, and go to a dry dock for repairs. Life was relaxed and while I performed my daily duties and assignments conscientiously, I had time to become quite a skilled bridge player and enjoyed playing on the ship's champion softball team.

In July of 1946, I received my orders for inactive duty. While I had considered staying in the Navy, I was told I could not receive the assignment I wanted. I had asked if I could be assigned to work in the Navy nuclear program. At that time, they were organizing for tests of various types of nuclear weapons in the Pacific, and I thought nuclear power was going to be an important part of the future. Because of my lack of background in nuclear matters, the Navy turned me down and I decided to accept my discharge. Again, a rejection from a requested course I had chosen proved to be the best thing that could have happened to me.

The Choice of a Civilian Career

A few months before my Navy separation, I began to investigate possible job opportunities. I wrote to Professor Eric Gross and other people seeking the options available to me. I decided that I would like to work with a utility on electric power, but I wanted a utility that would give me some excellent training. I applied to a number of utilities and had narrowed down my choices to two. One was Public Service Electric and Gas Company (PSE&G). They had an excellent cadet engi-neering training program which provided opportunities to work in every depart-ment in the company and learn the overall operation. The other choice was Atlantic City Electric where I could get an engineering position of broader scope. I decided to interview with both. The first interview was with Atlantic City Electric. Because of an out-of-date time table, I missed my train at Penn Station. I called Atlantic City and told them I could not appear for the interview but would arrange later for another one. The next day I went for my interview at PSE&G, liked their program very much, and decided to take an assignment as cadet engineer. Who knows what would have happened if I had gone first to the interview with Atlantic City? I might have liked that so much that I wouldn't have bothered to go to the PSE&G interview. Again, random events helped determine a major path in my life. Things that appear to be undesirable developments can turn out to be very desirable. These random events that occur can be caused by chance, but I am totally convinced that some of these events are caused by God who wants to see us take certain paths with our lives.

Work in Power Plants and with Line Crews

I began work at PSE&G around Labor Day, 1946, after taking a couple of weeks off to relax with my family. For the two years of the Cadet Program, I worked in generating stations, tracing out various circuits and lines. I worked in every department, testing boiler fluids and stack gases, repairing precipitators, maintaining transformers, etc. I worked in the control room and in the company laboratory calibrating instruments and performing various equipment and material tests. I worked in field divisions for distribution and for commercial activities.

During my stay at the field distribution division, I asked to be sent to linemen's school and there I spent four or five weeks, and became a qualified lineman. I gained an understanding of what it takes to be a lineman. This was in the days before "bucket trucks" when linemen used hooks to climb poles. I saw how high up one really is on top of a 40-foot pole swaying in the wind and depending on a safety belt. I realized the amount of strength needed to wrap wire to make a splice or joint by hand with a pair of pliers, how tired one can become after doing this kind of work for a few hours each day, and why it was necessary to take a little break on the ground and have a cup of coffee before going back up again. I am proud of the fact that I did qualify as a climbing lineman. I admit that I was never really very good at it, but I did do it.

Early Technical Assignments

During this cadet program, we had to undertake two projects and do reports on each. The two I picked were related to my hoped-for future career. I did a study on what would happen to power plants and to a generator unit, if the field were lost on the unit. This was a very comprehensive study and it got me involved with controls, reactive supply, heating of generator coils, etc. The second assignment I undertook was to investigate various approaches for determining the stability of generators. This enabled me to study the equal-area criteria and some of the standard equations and power angle diagrams that were used, as well as some of the other techniques used in evaluating stability.

I also had other interesting assignments while in the Cadet Program. PSE&G was interested, at that time, in increasing temperatures for the steam conditions in its new power plants to improve efficiency. It was not known what would happen to the standard engineering constants for various metals when they operated at these higher temperatures. For example, what were the moduli of elasticity for various types of steels when operated at higher and higher temperatures? What happened to the Poisson's ratios at these temperatures? All of these variations in the key ratios at higher temperatures needed to be known in order to do the boiler design. The PSE&G Chief Engineer gave me the assignment of investigating how and why these various ratios change. This led to several weeks of very interesting work, talking with many experts who had experience with measuring these constants at elevated temperatures.

I also had the interesting challenge of researching the basic parameters for design of an electrical reactor that was to be purchased by the company for connection to a new generator, where the generator leads would be tapped into the reactor and the power would flow out either end. The reactor was to be designed so that the reactance on each side of the tap would help balance the flow of power in accordance with requirements of the network. I used the standard equations for flux linkages and determining reactances that were in my circuit analysis and electrical engineering textbooks. After completing my design and turning in my recommendations, I had an uneasy feeling one night. I decided to re-read some of the material on which I based my calculations. I did so, and discovered that the equations I had used were valid only when there were no leakage fluxes. Since the design I had developed was for an air core reactor, and there would be significant leakage fluxes, I had to go back to my superiors and sheepishly tell them that my work was not suitable for the purpose intended.

They never did allow me to finish the work but I learned two things from the experience. One, when engineers do engineering work, they must always be re-thinking what they've done and how they've done it. By reviewing and mulling over, one may find mistakes and do a far better job. The second thing I learned is that it is not easy when one has made an error to go forward and admit it before action is taken based on your incorrect work. From that point on in my career, as a manager or supervisor, any time anyone came to me and said they had found an error in what they did, I always was pleased. I was not pleased that we had an error, but I was pleased that they had come forward and identified the error before it did any harm. I recognized that this was not an easy thing to do but good people will do it many times during their careers.

Electric Distribution Work and the Pride of Ownership

After completing the Cadet training program, I was assigned to the Bergen Division for two years where I worked in distribution engineering. I was responsible for planning and building distribution lines, troubleshooting during storms, and other interesting things. I enjoyed my work in the Bergen Division and the people I worked with. I found that the people who build the lines, the people who climb these poles, and the people who operate our substations and generating plants are very dedicated. While those of us who are engineers can conceive of concepts, ideas, and approaches, and while we provide an invaluable guiding service, the people who build things and operate things, and are perhaps less technically informed than we, are really the people who are responsible for our success. They take our ideas and put them to use.

I believe, in many ways, that the true greatness of America lies in those who build and operate our systems and our technologies. While in some cases, they are represented by unions that can be abusive, beneath these unions are human beings whose services and skills are invaluable. Only if we continue to recognize these talents, skills, and services, can our nation continue to thrive.

During my stay in the Bergen Division, I was responsible for laying out and monitoring reinforcements to all distribution circuits. I took to this work very quickly and was given considerable responsibility. One thing bothered me, however. I would develop a complete series of plans and recommendations for all the circuits; then a higher-level person from the Division would take them to the general office for approval. I found this very annoying. I felt that I had created these plans and I wanted to be involved in discussing them. This annoyance was not a minor one and it continued to fester in my mind until I talked directly with the Head of the Engineering Division. I told him that I thought it was essential that younger people should be allowed to follow through on the approval of their recommendations and not turn them over to others. I learned that I, and others, who had pride in our work wanted to receive recognition for it.

Because of this I always felt, in my subsequent work, that individuals should be allowed, no matter what their rank, to participate in discussions that involve their ideas. I practiced this while a manager in various levels at PSE&G, and I practice it today in my present business activities. It is important that as a society, we foster this pride of ownership as a motivating force among those who create ideas. Pride of ownership is not only a matter of proprietary ownership of a business; pride of ownership is essential in all creative thought. Individuals must receive psychic income for what they do as well as financial income.

Cable Systems, Connections and Discipline

After two years of service at the Bergen Electric Distribution Division of PSE&G, I was assigned to the general office in the underground engineering department where I was put in charge of rating all our subtransmission and transmission circuits as well as developing the rating formulae and policy for all distribution circuits. I was also responsible for the design of pot heads, splices, and other similar designs where the objective was to minimize the concentration of electric stresses.

I learned how cable thermal ratings were established. I began to review all of the ratings that were being used in system planning and operation for our subtransmission and transmission circuits. I discovered that many of these ratings were no longer up to date and were too high based on what was considered safe system operation. I started a review program and in a few weeks had revised many of these ratings. I sent out a letter with all of these revised ratings telling everyone throughout the company to use them in their work. There was an immediate and vigorous reaction. Individuals complained that they had done months of work using the old ratings and they had to go back and re-evaluate their load flow studies, re-set all of their operating limitations, and generally re-do work that had been done using the old ratings. They questioned the need for instituting revised ratings at this time. At an inter-departmental discussion, I demonstrated the incorrectness of old ratings, and the need for making changes. The decision was that the new ratings should be put into effect. There was grumbling for some time about the amount of extra work this caused, but thankfully those in authority recognized it was wrong to continue to use incorrect data in engineering work just because it made the job easier.

I discovered that it is not always easy to make necessary changes in data and procedures in a complex engineering operation, where many different people are involved in interrelated activities. The easy way out would have been to keep on using the old ratings. What might have happened if that had been done? Maybe nothing. Maybe there would have been some overheating of cables and some failures which could have not only damaged equipment but cut off service and perhaps even created human safety problems. An engineer is never sure of the effect of sloppy work. Again, my view is discipline is essential. You do the best you can at all times. If something is not as good as you can do it, you correct it. If it takes extra work and extra labor, you still do it over. I have written whole reports just to throw them in the wastebasket because further thought convinced me that it wasn't as good as I could do.

The Key Lesson

Many personal contacts throughout the industry and throughout the world were invaluable in shaping my ideas, helping me find solutions to difficult problems and generally leading to the achievements in which I have participated. An important lesson to learn is that without good people to work with, without good people to work for, without good people to work for you, and without good professional associates, an engineer is severely limited in what he can do and what he can contribute. As Ed Snyder, then Chairman of the Board at PSE&G, told me:

> *Always remember that those of us who live relatively glamorous lives, doing important things, traveling around the world, meeting with important people, and thoroughly enjoying our careers, are completely dependent on the many others who support us in many ways. We need to recognize this support and contribution and acknowledge it. We need to recognize the sacrifices that these other people may have made for the benefit of the group, the benefit of the project, and the benefit of some of us individually.*

My purpose in writing this Appendix has been to present such an acknowledgment to many individuals not named in the body of this book, along with some of the things that these individuals helped me learn.

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