NISTIR 6007

# Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation

## With Focus on Electrical Measurements for Transmission and Distribution

Gerald J. FitzPatrick
James K. Olthoff
Ronald M. Powell

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Electronics and Electrical Engineering Laboratory

May 1997



NIST

## YOUR COMMENTS INVITED

NIST invites your comments on this assessment of the measurement needs of the U.S. electric-power industry as that industry undergoes major changes during deregulation and seeks to adopt new technology. NIST regularly reassesses the needs of U.S. industries for measurement support in order to keep NIST's programs focused on the highest priority requirements.

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### Abstract

The U.S. electric-power industry, comprising the generation, transmission, and distribution systems throughout the country, has been described as the "greatest machine ever created". This machine is an integral part of the national infrastructure. Its continued good performance is vital to the success of the U.S. economy, to the pursuit of environmental and health goals, and to the assurance of safety and security.

Dramatic changes are now taking place in the U.S. electric-power industry as deregulation is implemented and as competition is introduced in providing electric power. These changes offer the possibility of lower prices for electric power and increased supply, with minimal increases in associated capital facilities. To achieve these goals in a competitive environment, the industry will have to exploit fully the capabilities of modern technology. To succeed in such exploitation, the industry will require new measurement capability.

This document describes the changes taking place in the industry. These changes are translated into technical needs associated with industry's response and then into the associated measurement needs for which NIST assistance will be required. The resulting measurement needs are grouped into categories by priority. The highest-priority needs are generally those with the greatest prospective economic impact.

This document focuses principally on measurement capability for the *electrical quantities* associated with the *transmission and distribution* of electric power. Special emphasis is placed on those measurement needs requiring the assistance of the National Institute of Standards and Technology (NIST). There are also important measurement needs associated with the efficient generation and use of electricity. They are the subject of other inquiries now underway at NIST.

The assessment presented here reflects NIST's current understanding of the key measurement needs, based on interactions with industry, universities, and government during the development of this document. Through publication of this document, NIST solicits additional feedback on the measurement needs of this industry. NIST's purpose is to assure that its resources are applied as effectively as possible in support of the U.S. electric-power industry and its customers nationwide.

### Keywords

competition; deregulation; electric-power distribution; electric-power generation; electric-power industry; electric-power transmission; electric utilities; electrical-equipment industry; electrical measurements; electrical quantities; electricity; measurement capability; metrology; utilities

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# PREFACE

## Purpose

This document describes the dramatic changes taking place in the electric-power industry as it undergoes deregulation. These changes are translated into technical needs and then into the associated measurement needs for which NIST assistance will be required. Comments on this assessment are invited and will aid NIST in focusing it resources on the areas of highest priority to the industry and its customers. These areas are generally the ones with the greatest prospective economic impact. While the focus here is principally on the measurement needs resulting from the major changes taking place in the industry, additional requirements of a long-standing nature are also discussed.

## Scope

The scope of this analysis may be characterized by describing both the industry covered and the types of needs addressed.

With regard to the industry covered, there are multiple participants of importance with multiple roles:

producers of electric power
- as equipment buyers
- as fuel buyers
- as electricity sellers
- as service sellers

end users of electric power
- as electricity buyers
- as electrical and electronic equipment buyers

electrical-equipment manufacturers
- as materials buyers
- as equipment sellers

This analysis focuses on the producers of electric power. They include investor-owned (private) utilities, government and cooperative utilities, and independent power producers. Together, they are considered here as the *electric-power industry*. Also addressed are the interactions of the electric-power industry with the other entities above.

The electrical-equipment manufacturers, which comprise the electrical-equipment industry, represent another important area for NIST to examine. These manufacturers supply equipment for the electric-power industry and for many other industries, such as the electronics industry, the building industry, the appliance industry, and the automotive industry. So the products of the electrical-equipment manufacturers are essential both to providing electricity and to applying electricity. The electrical-equipment industry, as it relates to the electric-power industry, is addressed here to a limited degree. The authors contemplate a follow-on effort focused specifically on the electrical-equipment industry and its measurement needs.

With regard to the types of needs addressed, this document focuses on measurement needs, including measurement methods, measurement reference standards, materials reference data, and calibrations services. Measurement needs associated with any technology supporting the electric-power industry have been considered. However, the focus of this analysis is on *electrical quantities* important to the *transmission and distribution* of electric power. Measurement needs associated with the efficient generation and use of electricity may be just as important. They are the subject of other inquiries underway at NIST.

*Transmission* describes the transfer of electric power from the generating sources at very high voltages, from 22,000 volts up to 800,000 volts, to central points of distribution or to other electric utilities [1]. *Distribution* describes the transfer of electricity from the central points of distribution to end users at voltages under 22,000 volts.

## Approach

The approach taken by the authors has three steps: (1) identify the driving forces behind the changes in the electric-power industry; (2) translate those driving forces into the technical needs that arise in responding to the forces; (3) translate those technical needs into the specific measurement support needed from NIST for industry's successful response. These three steps are addressed, one each, in the three chapters of this document.

This approach -- of moving from the broad driving forces to the specific measurement needs -- has the advantage of seeing the industry as it sees itself. Such an approach facilitates industry review and comment. It also facilitates identifying the highest priority needs by keeping motivation associated with response.

The complexity of the electric-power industry was immediately evident in the first stage of this process: the identification of the driving forces. The chain from cause to effect was not simple. For example, in some cases, one driving force (such as government deregulation of the utilities) gave rise to another driving force (such as economic competitive pressure). Nevertheless, the authors endeavored to create an order that kept cause ahead of effect as much as possible.

A variety of methods were employed to identify the technical needs and the implications for NIST, including: telephone discussions with industry representatives, face-to-face meetings, participation in industry conferences, publications and other reports, and discussions with NIST colleagues throughout the agency. There were many cross currents; for example, a given implication for NIST often appeared as a consequence of more than one driving force or technical need. These cross currents are reflected in this document.

From the broader list of implications for NIST, the nine most critical long-term needs and the three most critical short-term needs, associated with the transmission and distribution of electric power, are identified and discussed. NIST's current efforts, and especially those of the Electricity Division within NIST, are described. Both the importance of the work being conducted and the importance of the work remaining are described.

It should be noted that the industry itself is uncertain about the details of the changes that it will undergo in the next one, five, and ten years. Therefore, continued close contact with the industry, of the type employed during the preparation of this document, will be necessary to maintain a proper perspective on the needs and the associated priorities required for NIST's response.

## Audience and Technical Level

An effort has been made to make this document accessible to a broad audience, since readers from policy, management, and technical fields may be interested. However, the authors faced major challenges in handling the number of technical concepts inherent in a discussion of the measurement needs of the electric-power industry. The authors settled on the following approach. For Chapter One, addressing the broad driving forces underlying the changes in the industry, key technical concepts have been explained in the hope that the overall picture can be communicated successfully to all readers. For Chapter Two, on technical needs, the number of technical concepts that merited explanation was greater than could be accommodated in acceptable space. As a result, the authors included explanatory material selectively, that is, for the most fundamental technical concepts only. The authors hope that this approach will make this chapter accessible in the main to all readers. Chapter Three, on the implications for NIST, does not introduce new technical concepts, so readers who have braved Chapter Two will find themselves at home in Chapter Three.

## NIST's Role

NIST focuses on developing measurement capability that is beyond the reach of the broad range of individual companies and that will have high economic impact for the nation. Companies seek NIST's help for several reasons. The companies may need NIST's special measurement expertise, which extends across many fields of technology, for the development of new measurement capability or for the comparison or validation of existing measurement capability. The companies may need NIST's impartiality, which enables NIST's measurement solutions to be adopted by all companies in an industry with confidence. The companies may need NIST's imprimatur as the lead-agency of the U.S. Government for measurements, which enables NIST to support U.S. interests when measurement barriers bar U.S. products from foreign markets. Further information on NIST's role is provided, in detail, in Chapter 2 of *Measurements for Competitiveness in Electronics* [2].

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# INTRODUCTION

The U.S. electric-power industry is one of the largest industries in the United States. Electricity sales are $208 billion (1995) [3], and the industry employs 441 thousand people (1995) [4]. If the electric-power industry is compared with the manufacturing industries, its output falls between the third largest (automotive) and fourth largest (petroleum refining), as shown in Table 1 [5]. Further, electricity is an essential *ingredient* in the vast majority of products. About 1.3 percent of the value of the products of all manufacturing industries in the United States is attributable to the cost of the electricity used in making them (1994) [6].

**Table 1: LARGEST U.S. MANUFACTURING INDUSTRIES (1994)**

| Industry | Shipments ($billions) | Employment (thousands) |
|---|---|---|
| Electronics | 321 | 1,710 |
| Chemical | 316 | 842 |
| Automotive | 297 | 934 |
| Petroleum Refining | 123 | 75 (1992) |
| Aerospace | 95 | 552 |

## Installed Capacity and Consumption

The United States has the largest installed capacity for generating electricity of all countries in the world. This capacity is more than three times that of each of the next two most prominent countries in rank order; they are Japan and the Russian Federation. They have nearly equal capacity. The U.S. capacity is 770 gigawatts, or $770 \times 10^9$ watts (1994) [7].

The United States is third among the countries in the world in its consumption of electricity per person [8]. Canada is first and Sweden is second, with 57 and 30 percent higher consumption, respectively, than the United States. U.S. consumption is 13 megawatt-hours [9], or $13 \times 10^6$ watt-hours, per person per year (1994) [10].

## Changes in the Industry

This industry experienced rapid growth after its inception, followed by more steady growth. Today the industry is undergoing the most dramatic changes in over a century. These changes are organizational, economic, and technical in nature. It has recently been said that the "electric utilities are now the world's most turbulent industry" [11].

Because of the impracticality of having more than one electric-power provider in a given area, and because of patterns of historical development in the industry, the electric-power industry evolved into a system of regulated monopolies in the 1930s. In most cases this meant that the same electric utilities that generated electricity also transmitted and delivered the electricity to the customers. This approach is now being reconsidered. Although the details remain to be worked out, the utilities are in the process of being deregulated. The aim is to foster competition that will provide the most value for the price of electric service in response to the customers' needs. In effect, the utilities are being asked to make a transition from traditional vertically integrated organizations to new horizontally integrated ones. As the utilities look to streamline their operations, they are making efforts to increase the value of, and expand, the services that they provide. In this effort they are applying new technologies to their operating systems. These new technologies include optical sensors, power electronics, and microelectronic controllers, among others.

All of these changes are giving rise to a broad spectrum of needs for supporting measurement capability, and, therefore, for NIST's assistance, with high levels of prospective ecomomic impact.

These needs and the background for them, with focus on the electrical measurement needs related to the transmission and distribution of electric power, are the subject of this document.

# CHAPTER ONE: DRIVING FORCES

At the most general level -- the societal level -- the driving forces behind the changes in the electric-power industry, and their equipment suppliers in the electrical-equipment industry, take several principal forms. These driving forces can be divided into three groups, shown below. Those that are especially closely related have been grouped together and will be treated together in subsequent sections.

(1) Economic growth, economic efficiency, international competitiveness
(2) Environmental quality, health
(3) Safety, security

For the electrical-equipment industry, the driving forces in the first group have the typical interrelationship found today in many manufacturing industries. However, they have special importance with respect to economic leverage because electricity is a factor in the cost of the products of virtually every other industry. For example, General Motors estimates that the cost of electricity used in assembling an automobile averages $190 per vehicle, and that the inclusion of the cost of electricity used in the production of parts and materials yields $700 per vehicle [12]. Therefore, a significant reduction in the price of electricity represents a substantial savings and a potentially important improvement in the competitiveness of many product lines, and even entire U.S. industries.

The second group of forces (environmental quality and health) and the third group (safety and security) have historically represented social-impact aspects of an industry's activity. That is, they reflect how the industry's economic activity relates to society's well-being. However, as global environmental issues, safety, and other social concerns have received more attention and have become the target of increased legislation, these forces have increasingly affected the ability of an industry to compete [13].

In the discussion that follows, each of these three groups of driving forces is broken down into subordinate elements for closer consideration.

## 1. ECONOMIC GROWTH, EFFICIENCY, AND COMPETITIVENESS

### 1.1 Government Driving Forces

#### 1.1.1 Deregulation of the utility industry

The deregulation of the electric utilities began essentially in 1978 when the passage of the Public Utility Regulatory Policies Act (PURPA) required the electric utilities to purchase electricity from independent power producers. Deregulation activities continued in the 1980s, when the U.S. Government actively, and ultimately successfully, pushed for the break-up of AT&T which was the world's largest integrated utility. This action was soon followed by the deregulation of the natural gas industry by the Federal Energy Regulatory Commission (FERC), permitting more choices for local gas utilities and large gas customers.

Pressure for similar deregulation in the transmission segment of the electric utilities then increased due to the wide disparities in electricity prices between different parts of the country. Residential rates for electricity, for example, range from about 3¢ per kilowatt-hour in parts of the Pacific

Northwest to about 16¢ per kilowatt-hour in the New York City [14]. Pressure to deregulate local utilities at the state level has been particularly strong in some states, such as Illinois, where rates charged by neighboring utilities can differ by as much as a factor of two. In this environment, and at a time when new, inexpensive sources of electricity generation were being developed and marketed, the 1992 National Energy Policy Act (NEPA) was passed. NEPA provided for increased competition in the sale of electric power [15, 16]. As characterized in *Industry Week* [17], NEPA: (1) authorized municipalities to purchase electric power from the provider of their choice; (2) required local utilities to *wheel in* (transmit) this power over their electrical grid systems; and (3) required the local utilities to buy available electricity from independent power producers. [*Wheeling* is the transmission of large amounts of electric power over long distances among a number of independent sources of electricity.] In addition, NEPA encouraged state regulators to "foster competition and greater reliance on market mechanisms" [17]. In April 1996, federal regulators enacted rules expanding these requirements by mandating that the utilities allow their competitors to use the utilities' own transmission lines at competitive rates [18].

While NEPA opened the door to increased competition within the electric-power industry, it by no means completely determined the extent of this new competitive environment. In fact, the industry has been described as currently residing in an undefined "twilight zone" between a regulated monopoly and a fully competitive state [15]. This mixed state is reflected in the following combination of requirements: the utilities must still provide electricity to all customers; but they must also provide transmission and distribution access to independent power producers and competitors. Nevertheless, customers of the utilities are still captive to a significant extent, even though they now have some additional choices, such as generating their own electricity or attempting to force wheeling.

While the regulatory state of the utilities is somewhat undefined at present, the expected result of NEPA is the end of monopoly control for the affected power producers, the end of price setting based on the demonstration of increased costs to regulatory bodies, and the emergence of price competition in the sale of electric power. Fully implemented, NEPA could enable customers to choose from whom they buy their electricity, and the level of service that they require. California moved toward this possibility in April 1994 when the California Public Utilities Commission proposed new regulations allowing all electric-power consumers, including homeowners, to select their supplier by 2002 [19]. Illinois is considering similar regulations that would go into effect in 2000 [20].

The implementation of such deregulation is seen by many as being achievable only if the utilities are *unbundled*, that is, if the basic services currently offered by utilities (generation, transmission, and distribution) are separated into individual companies. Each company would offer a range of possible customer service options including varying degrees of power quality, back-up, maintenance, and guaranteed reliability [15]. Something similar to this arrangement was recently implemented in the centralized, government-owned electric utility in the United Kingdom. In 1990 the United Kingdom's system was restructured and partially privatized to form separate generation, transmission, and distribution companies. Under the new system, medium-to-large users of electricity have been able to select their electricity suppliers since 1994, and all customers should have this capability by 1998 [21]. While it is still too early to tell if the increased competitive arrangement in the United Kingdom has resulted in lower consumer prices, it is apparent that this arrangement of unbundled utilities does work. This change has also led to purchases of regional utilities by foreign companies. It should be noted, however, that the present arrangement in the United Kingdom is far from unregulated. In fact, the United Kingdom's system represents perhaps the most complex regulatory system in the world. This complexity results from the effort to ensure that the independent companies which make up the utility system provide fair and reliable delivery of electrical power to the country.

One of the most challenging aspects of applying a similar system to the United States is related to the vast and complex transmission and distribution system in place in North America. Presently, there are more than 3000 independent entities (owned primarily by utilities) that make up the transmission system in the United States and Canada [22]. This system comprises 672,177 miles (1995) of overhead high-voltage transmission lines operating at 22,000 volts or higher [23], and has been referred to as the "greatest machine ever created" [14]. Adding to the complexity of the situation is the fact that these systems are all designed to provide a support service, or foundation; that is, they were never intended to make money independently. The questions of who owns and controls this network is key to the future development of the competitive electrical system in the United States.

Under the current operating system, wheeling is very complex. On the one hand, the sale of power from one utility to another is common; nearly 40 percent of all electricity produced by utilities in the United States is sold to another utility [19]. But on the other hand, the sale of electricity that must flow through several transmission systems to complete the transaction is neither common nor routine. The underlying difficulty is that power flow follows the laws of physics and not of contractual obligations [24]. This makes it difficult to determine whose transmission system carried the power, and who should be paid for the service. This difficulty is one of many technical, legal, and economic challenges that must be addressed as the U.S. electric-power system moves toward deregulation.

The trend toward deregulation of the industry suggests that the utilities may soon be competing against each other for the same customers. This implies that the utilities which offer acceptable services at the lowest prices will be the most successful; these pressures will drive the development of new and cheaper methods of generation, transmission, and distribution [25, 26]. Further, it can be expected that a wide range of new services may be developed and offered to customers to attract their business. Some of these services may include real-time pricing, demand-side management, and guaranteed power delivery. These services, and their technical implications, will be discussed in later sections of this document.

#### 1.1.2 Reduction in Federal support for utility industry

The future of significant federal funding for projects supportive of the electric utilities is increasingly in doubt. While DOE retains substantial programs in large-scale generators, such as nuclear power and clean coal technologies, support for smaller-scale technologies is limited. Programs exist for fuel cells ($50 million), photovoltaics ($60 million), and superconducting cables ($20 million) [27]; but the entire DOE program on transmission and distribution technologies was zeroed out in 1995. The National Science Foundation's entire budget for power-system engineering is only $3.5 million. This reduction in support during a period when so many changes are taking place within the industry only intensifies the need for adequate long-term measurement support from NIST.

### 1.2 Market Driving Forces

#### 1.2.1 Emergence of independent power producers and separation of producers and distributors

The electric-power industry comprises generating facilities from three different categories of ownership, as shown in Table 2 [28]. In terms of the percentage of electricity generated in the United States, the most significant category by far is the investor-owned (private) electric utilities. That category is followed in significance by the utilities owned outright by Federal, state, municipal governments, or those financed by the U.S. Government's Rural Electrification Administration and cooperatively owned. The remainder are organizations that are independently owned. They generate electricity either as a main product, or as a by-product of making something else. They are collectively referred to by the Edison Electric Institute as the *non-electric-utility-industry facilities*. They will be referred to here as the independent power producers. The data in Table 2 capture only that part of their output that is passed through the electric utilities. An example of an independent power producer whose data would be captured is a brick manufacturer that uses high-temperature exhaust heat from brick kilns to generate electricity and then sells that electricity back to the utilities.

**Table 2: ELECTRIC ENERGY GENERATED, BY FACILITY OWNERSHIP (1975 and 1995)**

| | Percentage | |
|---|---|---|
| **Owner** | **1975** | **1995** |
| Investor | 74 | 69 |
| Government/Cooperatives | 22 | 19 |
| Independent | 4 | 12 |
| | 100 | 100 |

Table 2 indicates that the most significant change in the distribution of electric-energy generation among the providers, from 1975 to 1995, is the growth of the independent power producers. The electric energy that they supplied tripled over the period, as a percentage of the total. The resulting growth in the number of suppliers of electricity, and the increased complexity that this growth introduces into the power grid, heighten concerns about both the quality of the electric power provided and the reliability and stability of the overall system.

The independent power producers are emerging as significant contributors to the electric-power industry for at least two reasons: deregulation and economic efficiency. Each is discussed below.

**Deregulation:** The Public Utilities Regulatory Policies Act of 1978 encouraged the creation of independent power produces [29], and an increasing number of them are entering the marketplace, providing a diversity of *alternative energy sources*. Unlike many of the conventional power producers, they do not own distribution or transmission systems; but they do want access to them. This change increasingly separates power producers from power distributors. It also underscores the problems of operating existing transmission systems within their present physical constraints, as the number and complexity of transmission services increase [29].

**Economic efficiency of the provider:** The development of highly efficient gas-turbine generators, combined with relatively inexpensive sources of natural gas [15], has led to an end of the economies of scale that the utilities have relied upon for many decades [29]. Previously, it was prohibitively expensive for a private company to generate a moderate amount of electricity, when compared to the cost per kilowatt-hour of electricity produced in the gigantic power plants of the utilities. Now small and moderate size gas-turbine generators can produce electricity cleanly and safely at a cost equal to or below that of many local utilities, resulting in a substantial increase in the number of independent power producers competing with established utilities. In fact, independent power producers account for half of all new power production capability that is being put into service in the United States [29]. Small, low-cost generators have also led many large electricity consumers to construct their own primary generating plants on their production sites, thereby eliminating the need to buy electricity, and in some cases allowing them to sell electricity back to the local utility at a profit [30].

### 1.2.2 Reduction of research and development expenditures by the electric utilities

The electric utilities, in the face of increasing competition, are cutting back on their investments in internal research and development. They are also cutting back on the research and development that they have collectively supported through the Electric Power Research Institute (EPRI) and other cooperative research organizations. EPRI's budget has fallen from $600 million to $450 million in the last few years [27]. At this time, electric utilities commit less than 0.5 percent of sales revenues to research, which is significantly lower than many other industries [14].

### 1.2.3 Change in role of EPRI

EPRI, the largest U.S. cooperative research organization dedicated to the electric-power industry, is experiencing a number of interrelated changes that will affect both the quantity and type of deliverables that it can provide in support of the electric utilities:

(a) reduced level of funding from its members and thus a smaller research program

(b) shift from a predominately long-range focus for research to a predominantly short-range focus

(c) change in its method of financing for specific projects

More specifically, on point (c), EPRI's core program will continue to be predominantly long-range in character and will continue to be funded by all of its members; but the size of this core program will be small. Its other research efforts, funded by subgroups of its members, will be larger than the core program, and the outputs will be provided only to the funding subgroup. Additionally, further break-ups, or unbundling of the utilities will increase the difficulties of EPRI in serving its members, due to their increased diversity [25].

EPRI has historically addressed issues of environment, national productivity, public safety, and the relationship between the utilities and the overall quality of life of their customers [25], in other words, areas of research that are too big for any single utility to address effectively. It is reasonable to ask whether these issues can be expected to be addressed by the individual utilities within the developing competitive environment.

### 1.2.4 Control of capital costs for the utilities

Electrical power equipment is expensive. For example, the cost of a single power transformer may exceed $500,000. The industry is, therefore, strongly motivated by economic forces to minimize capital investments in at least two ways.

**Extending system lifetimes:** Many power systems are nearing the end of their design lifetimes. Replacing part or all of these systems is very costly and in some cases, such as nuclear power plants, nearly impossible due to regulatory requirements. For example, the regulatory requirements for decommissioning a nuclear power plant can exceed the costs of operation. With increasing evidence that many systems may be able to exceed their design lifetimes by considerable margins, the need has arisen for methods to predict and monitor those extended lifetimes. There is a tremendous economic incentive for the development of these methods. Diagnostic methods are currently being developed for testing of power generators [31], cables for nuclear power plants [32], and other electrical equipment, such as transformers and power cables.

**Minimizing new construction:** Minimizing the construction of new power stations and transmission systems, while continuing to provide required services to a utility's customers, substantially improves the competitiveness of the utility. This can be done in at least three ways:

(1) *Limit the growth in demand for electricity through increased efficiency of end-use devices, such as motors, lights, etc.* [33]. Many utilities currently have demand-side management (DSM) programs which encourage the use of energy-efficient equipment through some monetary incentive. In fact, the American Public Power Association has referred to these types of programs as "the quiet revolution" [34], because of the large number of utilities that are offering these programs [35]. The potential for saving of electricity by using energy-efficient equipment is quite large, and a significant effort is being expended to accomplish this goal. For example, the city of Springfield, Illinois is in the process of retrofitting all government-owned buildings with energy-efficient lighting, reducing the demand for electricity by a full megawatt [36]; these savings benefit the taxpayer and the local utility. The fact that 80 percent of all electricity in the United States is used for motors, space conditioning (i.e., heating and air conditioning), lighting, and refrigeration [37], implies that a concerted effort to improve the efficiency of equipment in these areas could provide significant payoffs. The use of devices of increased energy efficiency is also beneficial to the environment, as discussed later in this document.

(2) *Reduce the extremes in demand through the limitation of peak loads since new power generating systems are first required to cover new peak load.* Reductions in peak loads can be aided by types of demand-side management at homes and businesses, including real-time pricing (that is, charging the customer what it really costs at that instant to provide the required electricity) and customer load control by the utility (for example, the ability of the utility to temporarily turn off a customer's hot water heater or air conditioner during peak hours). These types of programs are currently in their infancy, but they are expanding rapidly. In 1992 the U.S. utilities spent over $2 billion on demand-side management programs. That type of investment is expected to increase to over $30 billion by the end of the decade [37]. Pacific Gas and Electric has stated that it expects to meet 75 percent of its anticipated new demand by the year 2000 through demand-side management programs [38]. Real-time pricing (RTP) is one of the most promising new methods to lower peak electricity use, as evidenced by the fact that 14 utilities have started RTP programs [4]. However, these programs are presently limited by the fact that RTP requires interconnected power metering for the customers. Such metering requires a significantly more developed communication system between the utility and the customer than is presently available [39]. Such systems are currently practical only for a utility's largest users.

(3) *Achieve full utilization of all power delivery systems.* This last item is most applicable to transmission lines and distribution systems. Great economic benefit can be obtained by transmitting power more efficiently through existing lines. Transmission systems now carry loads at 70 percent or more of their capacity less than 20 percent of the time. A similar 70 percent or more capacity utilization for distribution systems occurs less than 5 percent of the time [14]. It is possible for existing power delivery systems to accommodate increases in total power delivered without increasing their capacity limits. In addition, power delivery systems can be made more efficient by optimizing their operation. Improvements will require new methods of power-flow control technology. A related method is the implementation of artificial-intelligence systems that could control a transmission network in such a way as to allow greater transmission capacity [40]. Also possible is the operation of power equipment (such as generators and transmission lines) with reduced safety margins for short periods of peak demand, but with corresponding reductions in allowed lifetimes [41].

### 1.2.5 Control of operating costs for the utilities

The pressure to reduce operating costs continues to have important effects on the utilities. Improved efficiency can be pursued through improvements in generation, transmission, and distribution. This emphasis has led to a new practice within utilities of *benchmarking* their performance. Benchmarking is the use of comparisons to other utilities to determine a given utility's competitive performance levels [42]. The goal is to determine where a utility is performing efficiently, and where improvement is needed. The development of these benchmarks is a continuing process, and is being pursued aggressively by the utilities.

The marginal cost of producing power increases by 20 to 50 times during periods of peak demand [19], so it is to the advantage of the consumer and the utility to reduce peak demand relative to average demand. Therefore, significant improvements in the control of operating costs can be achieved by reducing peak demands, which also minimizes the need for the construction of new generating capacity, as discussed in the previous section. The effectiveness of this approach is reflected in the estimated 2000 megawatts of load, or approximately 4 percent of peak demand, that is shed on a voluntary basis by users during peak periods in the United Kingdom [43], where demand-side management programs are being actively promoted.

The most common approach to cost savings currently being pursued by the utilities is reduction in the number of personnel. Staff levels of utilities today are 10 to 20 percent lower than peak levels in 1986, and reductions of 20 percent more [42] are expected to occur eventually in almost all job categories. These continuing reductions imply a greater reliance on automation in the future, which suggests the increasing need for highly developed communication networks, diagnostic controls, and artificial intelligence systems.

#### 1.2.6 Internationalization of markets for electric utilities

The 1992 Federal law that opened the domestic U.S. electricity market to competition, also allowed U.S. utilities to make investments abroad more easily [29]. This freedom enables U.S. utilities to purchase or operate utilities in foreign markets. Many U.S. utilities are embracing this opportunity by buying profitable foreign utilities as a means of ensuring continuing profits and competitiveness in spite of growing uncertainty in the domestic electricity market. The largest and most recent acquisition of this sort is the purchase of Britain's South Western Electricity Board by The Southern Company [44].

It is anticipated that by the year 2010, 47 percent of all new electricity usage will come from the world's 100 developing countries [45]. This represents a huge potential for sales of equipment and services, and represents a gigantic electricity market that is as yet untapped. In many cases, the U.S. utilities are now utilizing their extensive experience and their reputations for reliable service in acquiring contracts with foreign governments or regulatory bodies to build, operate, or oversee these installations. The question of reliable performance is very relevant in the foreign market, particularly in developing countries, where World Bank statistics show that, on average, 40 percent of all electrical production capabilities are unavailable for service at any given time [46]. Examples of U.S. utilities that are already operating power systems in foreign countries include Duke, Entergy, and Mission Energy, who have bought transmission networks in South America and Asia, and who are now managing these systems with guaranteed performance to the host country [42]. Similarly, Southern Electric International has recently negotiated the purchase of a 49 percent equity in the power-generation facilities of Trinidad and Tobago [47].

An alternative form of international competition is the sale of electricity across international borders. This form of competition is becoming more common in Europe with the European Union countries exporting/importing over 100,000 gigawatt-hours of electric power annually [48]. This trend of selling electricity to other countries is also occurring in Latin America as utilities are privatized, and as commercialization is being encouraged [49]. At the present time, this type of competition is not a major concern to the U.S. utilities since Mexico and Canada represent the only practical sellers/buyers of electricity to the United States; and the amount of electricity being exported/imported is very small [49, 50]. In fact, Ontario Hydro has expressed its concerns over the negative implications of Canada becoming a significant source of electricity for the United States [50]. It is important to note that even though the amount of electricity that crosses the U.S.-Canadian and U.S.-Mexican borders is small, this exchange is important since it is usually in response to emergency needs of a particular utility or geographical area. In the winter of 1994, the importing of electricity from Canada is credited with preventing several severe power outages in the northeastern United States due to extreme weather conditions [51].

### 1.2.7 Internationalization of markets for electrical equipment

U.S. utilities bought only $15 billion of electrical equipment in 1988, compared to $50 billion in 1980 [52]. In contrast, the developing countries will buy an estimated $1 trillion of electrical equipment in the 1990s [46], or about $100 billion per year. Countries like China now represent the world's largest market for electrical equipment with more than 170 gigawatt-hours of additional capacity to be built within the next ten years [52, 53]. These facts clearly show that the market for electrical equipment is no longer focused on the United States. Markets and suppliers for electrical equipment are becoming increasingly internationalized. The passage of free trade agreements, such as GATT and NAFTA, will serve to increase further this internationalization and competition [45]. Recognition of national governments of the importance of this marketplace has led to government support for national competitive positions in some countries, further intensifying the competitive pressures on other nations. Several sectors of the U.S. electrical-equipment industry are showing the negative consequences of very successful international competition [54]. Other U.S.-based companies have risen to the competitive challenge and have made significant advances in selling their products to countries with growing electrical markets. General Electric, for example, has received more than $3 billion in power-system orders from Asia in the last two years [53].

This globalization of trade results in a world market in which equipment testing is governed by international standards. Consequently, the United States must have access to the same measurement capability used elsewhere in the world to verify test results and to enable U.S.-made products to compete in the world market. Also of concern is the possible lead-time advantage for those nations with measurement expertise. Further, the United States should have a role in creating international standards (through the International Electrotechnical Commission [IEC]). There are concerns about the possibility that the desires of a few multinational companies may lead to standards that result in trade barriers [52].

### 1.2.8 Continuing growth in demand for electricity

The demand for electricity has continued to grow in spite of major improvements in the efficient use of electricity. Electricity sales reflect this demand. They increased at a compound average rate of 2.3 percent per year from 1990 to 1995 [55]. Population growth is one important factor in increasing this demand. Another factor is a technical characteristic of electricity itself: versatility in application and convenience in control. As a result a never-ending array of new products emerge that employ electricity.

## 1.3 Technology Driving Forces

The *emergence of new technology* is not a primary driving force for change in the electric-power industry. That is, there is no obvious, new, ground-breaking technology whose existence mandates a profound change in the electric-power industry [27]. Rather, forces such as deregulation and competition are primary. This situation contrasts, for example, with the telecommunications industry, which was revolutionized by the emergence of fiber-optics technology, acting as a primary driving force. A technology driving force that would be primary for the electric-power industry would be the emergence of practical superconducting equipment and transmission lines. (That possibility is discussed in detail in the next chapter.)

In contrast, the *adoption of new technology* is essential to a successful response by the electric-power industry to the primary driving forces. For the electric utilities, the upcoming changes are also an opportunity to innovate in ways that in the past were perhaps not economically necessary or feasible. In fact, so important is the adoption of new technology to this industry that the present has been described [25] as the "dawn of a new age of technology" for the electric utilities. The president of the Power Engineering Society of the Institute of Electrical and Electronics Engineers (IEEE) has said that in the future, the most competitive utilities will be the ones employing the most advanced technologies [26]. As a result, it has become clear that "contrary to popular conception, the technology employed and needed by the electric-power industry is not mature" [39].

Some of the many new technologies that will have an impact on the electric-power industry, now that other forces are driving change, are listed below, as examples. These and many more are discussed in Chapter Two, which is devoted to technical needs.

### 1.3.1 Information technology

Improved communication capabilities will be necessary for many demand-side management services. These services include the automation of distribution of meter reading, as well as other services for information-exchange between the customers and the utilities [56]. Improved communication capabilities will also be necessary for monitoring and controlling transmission and distribution systems.

### 1.3.2 Power electronics

Considerable growth is occurring in the use of the relatively new technology of power electronics for diverse applications, such as control and power conversion (principally ac to dc), and especially for maintaining power quality, and for improving the efficiency of electric-power delivery.

### 1.3.3 Optical fibers

Optical fibers are promising as sensors in electrical environments because they are non-conducting, capable of linear sensing along their lengths for some applications, versatile in the number of parameters they can measure, and sensitive.

#### 1.3.4 Artificial intelligence

Artificial intelligence (AI) systems are now becoming sufficiently sophisticated that they can be used to aid in power system design and control [40]. Uses for AI and expert systems include fast restoration of power after a fault, maintenance of optimal power flow, and load management.

#### 1.3.5 Satellites

Satellites are already used for timing control in power networks and may increase in importance as wide-area networks, in particular, emerge. The Global Positioning System (GPS) is already being utilized to determine the location of lightning strikes by supporting synchronized measurements.

## 2. ENVIRONMENT AND HEALTH

At the end of 1990, over 100 environmental laws were in place that affected the operation of the U.S. electric utilities [57]. The Edison Electric Institute estimates that nearly $40 billion will be spent by the utilities to comply with existing federal environmental laws [58]. This trend of growing legal restrictions on the operation of utilities will most likely continue in the future, and may in many ways drive the future technological developments required by the utilities. The two most obvious manifestations of growing litigation surrounding utility operation are in the areas of (1) limitations on land use due to the proximity of population centers or wildlife, and (2) concerns about pollution, including that associated with electric and magnetic fields. Both of these areas are discussed below.

### 2.1 Land-Use Limitations

The utilities face land-use limitations in locating power substations and in obtaining rights-of-way for new power lines. As a result, the utilities pursue increases in power density in existing rights-of-way and power substations. The methods used often employ higher voltages and currents and, therefore, give rise to increased concern for component lifetime and reliability, and for environmental effects from electric and magnetic fields. Other methods involve: (1) the use of a dc line in parallel with an ac line to permit stabilization of the ac line while it runs closer to its maximum capacity than would otherwise be acceptable; (2) special configurations of lines and higher number of phases, both to increase power transmitted and to decrease field effects; and (3) increased use of underground transmission systems, including new superconducting systems.

### 2.2 Pollution Concerns

#### 2.2.1 From electric-power generation

Most electricity in the United States is generated by burning coal, as shown in Table 3 [59]. The second most important source, nuclear, is about one-third as significant. Over the period from 1975 to 1995, the relative significances of the energy sources shifted significantly. While coal dominated throughout the period, the relative contributions from gas, hydro, and fuel oil dropped off sharply as coal and nuclear sources picked up. However, in the recent period from 1990 to 1995, the relative significances of the energy sources remained largely unchanged, with no energy source changing more than 3 percentage points.

Concerns over pollution from the production and distribution of electricity continue to be a major public issue. Possible pollutants include electric and magnetic fields, air and water-borne emissions, insulating materials, global warming gases, radioactive waste, and decommissioned nuclear power plants. Concerns expressed over exposure to electric and magnetic fields have prompted epidemiological studies that have produced conflicting results, but which have also greatly affected the public perception of the risk of living near power lines [60]. The questions of health-threatening emissions have also received considerable attention, particularly with regard to $NO_x$, $SO_x$, and $CO_2$ emissions from coal-burning plants [58]. Coal is intrinsically the least clean fuel, and it dominates U.S. energy generation. Emissions from coal-burning plants are of particular world-wide concern because of the anticipated increase in electricity production in developing countries. At present, 25 percent of the world's electricity is produced by developing countries, and this percentage is expected to increase to 70 percent by 2025 [46], mostly through increased burning of coal. This change has huge implications for pollution and related global warming. Additionally, concerns have recently been raised over the release into the atmosphere of sulfur hexafluoride ($SF_6$) because of the high global-warming potential and the long lifetime of $SF_6$ [61, 62]. $SF_6$ is a gas used as electrical insulation in devices such as circuit breakers and other electrical equipment in substations.

**Table 3: ELECTRIC ENERGY GENERATED, BY FUEL SOURCE (1975 and 1995)**

| Fuel | Percent 1975 | Percent 1995 |
|---|---|---|
| Coal | 44.5 | 55.2 |
| Nuclear | 9.0 | 22.5 |
| Gas | 15.6 | 10.3 |
| Hydro | 15.6 | 9.8 |
| Fuel Oil | 15.1 | 2.0 |
| Other | 0.2 | 0.2 |
| | 100.0 | 100.0 |

More generally, concern over the environmental impact of power production has led to an increased desire to develop renewable energy sources. These sources include photovoltaics, wind, biofuel, solar thermal, geothermal, and fuel cells. Photovoltaic cells are perhaps the most versatile and technologically mature of these alternate sources. Yet, these cells account for only 300 megawatts of production annually, although they have a growth rate of approximately 20 percent per year [39, 63]. Recently, 68 utilities formed a consortium to develop this technology further for wide spread use [64]. Similar developments can be expected in an effort to tap these other renewable energy sources.

### 2.2.2 Abated through use of electricity

Reducing pollution by turning to electrical power in place of direct use of gas, oil, or coal has recently become an important issue, and will tend to drive some of the anticipated increases in electricity usage. This driving force underlies the emergence of electrical vehicles, mandated by some states for upcoming years. The recharging of electric vehicles will present significant additional loads for the electric utilities, approximately 7.5 billion kilowatt-hours per year for 1 million electric vehicles [39]. The concept of replacing small internal combustion engines with electric motors is attractive since electric motors derive their power from central power plants that: (1) use domestic resources to produce power; (2) utilize centralized, high-quality pollution-control techniques; and (3) make efficient use of surplus or off-peak electricity [65]. Considerable savings in pollution levels are also obtainable by converting many other processes and devices to electricity, such as lawn mowers, steel manufacturing, heating, and high-speed electric trains [37].

## 3. SAFETY AND SECURITY

Power interruption and degradation in the quality of electricity have major safety consequences as well as major economic consequences. Minimizing both of these remains a continuing concern for the electrical-equipment manufacturers and the power providers. However, the anticipated breakup of the vertically integrated utilities functioning as regulated monopolies raises the questions of who is responsible for reliability and who pays for it. For an industry whose reliability has been almost unquestioned for the past 50 years, these are extremely important questions. Also, as mentioned previously, the development of electrical devices that are increasingly sensitive to power fluctuations makes the stability and reliability of the power system perhaps the most important technical issue to be addressed in the near future by the utilities [14].

### 3.1 Reliability and Stability of the Power Network

Reliability and stability have long been hallmarks of the U.S. electric-power system. Maintaining that enviable record in the face of major changes in the industry, designed to produce positive economic effects, will be a significant challenge.

Here are examples of some of the changes that will complicate maintaining the reliability and stability of the power network. The emergence of additional suppliers of electric power increases the complexity of the power system. The economic pressure on the providers of electricity prompts them to use aging equipment longer. The environmental restrictions on right of ways encourage sending more power down existing rights of way. More generally, the emergence of wide-area power sharing and power wheeling complicate control and stability issues.

These complications give rise to the need for automated transmission and distribution systems to provide adequate control. These new systems will likely employ new control technology including optical sensing and solid-state devices in ac environments to bring major sources on and off line, and to control current flow in transmission and distribution systems.

### 3.2 Power Quality

Power quality, too, has long been a hallmark of the U.S. electric-power system. However, maintaining that quality has become increasingly difficult. Power quality is complicated by many of the same factors that complicate reliability and stability. But there are two additional factors of major importance: the sensitivity of microelectronic devices and the emergence of power-electronic devices.

The proliferation of microelectronic devices, in everything from personal computers to manufacturing-process controllers, has radically changed end users' views about the quality of electric power. These devices can be easily damaged by disturbances in the power systems. In the past, minor power disturbances were usually evidenced only as a brief dimming or flickering of room lights. Today, power disturbances have much more dramatic consequences. A momentary disturbance can produce effects ranging from the inconvenience of resetting digital clocks (blinking-clock syndrome) to the loss of an entire batch of silicon wafers at a semiconductor fabrication facility. Preventing such a loss at a semiconductor fabrication facility requires virtually perfectly dependable electric power for a three-week production cycle [14]. As a further example, corporate data-processing centers can usually justify a 45 percent increase in capital expenditures as part of the construction of power systems, in order to ensure power quality [66, 67]. The question of who is responsible for the quality of power used, the utility or the consumer, is an important one.

A second factor is the emergence of the technology of power-electronic devices. They can be the source of significant power fluctuations. Power-electronic devices are used increasingly in electrical and electronic products to achieve high energy efficiencies and excellent control. In normal use, they switch on and off rapidly to control power flow. The resulting transients can be propagated on power lines to other users and can degrade the smoothness, or quality, of the sinusoidal waveform that the power producers wish to deliver. At the same time, power electronic devices, when employed by the providers of electric power, are an important part of the solution part to both power-quality and reliability and stability problems.

## 4. SUMMARY

All indications are that the electric-power utilities are entering a period of significant change. That change is driven by forces in at least three broad categories: (1) economic growth, efficiency, and competitiveness; (2) environment and health; and (3) safety and security. Within these broad categories, the most important driving forces are deregulation and the economic competition that it is promoting. To respond to these changes, and thus to remain competitive and profitable, the providers of electric power are being forced to adopt new technologies.

Where these changes will lead, and what the electrical-power industry will look like in the years to come, is difficult to predict. However, it is already clear that these changes will give rise to a broad spectrum of technical needs and to related requirements for new measurement capability, as the next two chapters will show.

# CHAPTER TWO: TECHNICAL NEEDS

The societal driving forces for the electric-power industry, described in Chapter One, give rise to distinct technical needs associated with the response of the electric-power industry. In Figure 1, the societal driving forces are shown in the first column. In the second column, the societal driving forces are translated into drivers of primary importance to the electric-power industry, such as efficiency and power quality. These drivers, in turn, give rise to a variety of technical needs that are shown in the third column. Finally, these technical needs can be addressed with a variety of technology solutions that are shown in the fourth column.

The structure for this chapter is derived from the second column of Figure 1. That is, the drivers for the electric-power industry form the basis for organizing the discussion of the technical needs. However, the drivers of efficiency and reliability/stability have been grouped together to form Section 1 of this chapter. This has been done because they give rise to some important common technical needs, as Figure 1 shows. Section 2 discusses trade. Section 3 focuses on the environmental issues of global warming and health effects. Section 4 addresses the remaining topic from safety and security, which is power quality.

There are a number of cross currents evident in Figure 1. A given technical need may result from more than one of the drivers in the second column. For example, the technical needs for *real-time control of power networks* and for *improved component reliability* derive from both *efficiency* and *reliability/stability*. Similarly, the technology solutions in the fourth column may serve more than one technical need. For example, the technology of *power electronics* provides solutions to the technical needs for both *improved power-transfer efficiency* and *mitigation of harmonics*. Not all possible cross currents are diagrammed in Figure 1, just the principal ones, for clarity in the resulting presentation.

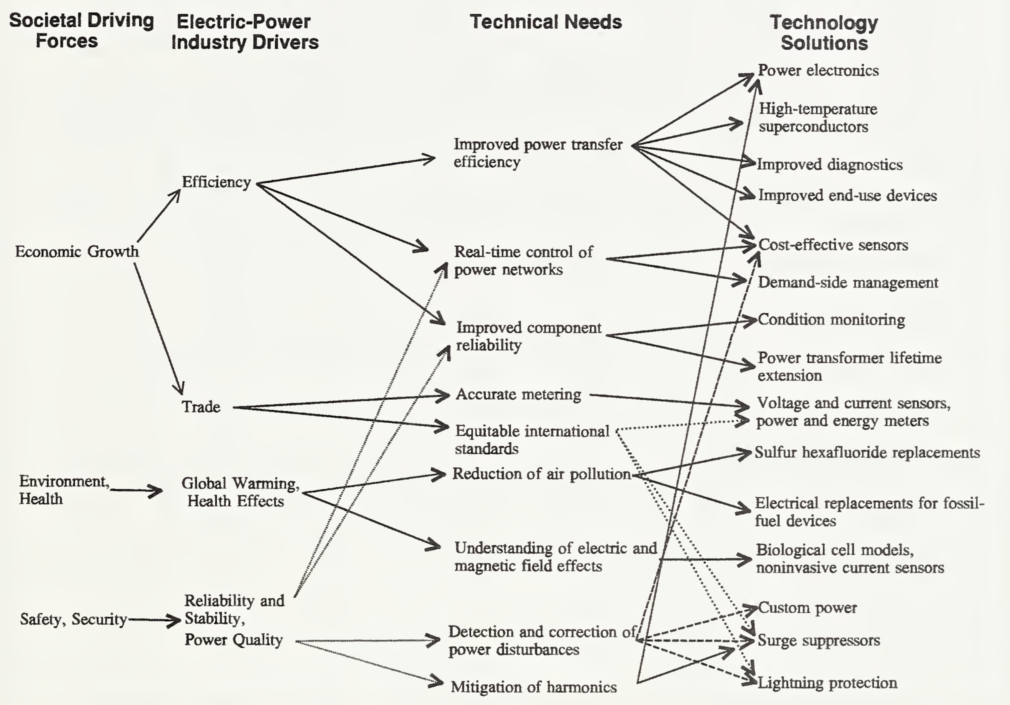
With an understanding of these cross currents, the technical needs are discussed in this chapter in the order shown in Figure 1. Then in Chapter Three, the role of NIST in supporting the technology solutions is examined.

The following discussion focuses principally on the transmission and distribution aspects of electric power. Important issues also surround the generation and use of electric power; they are the subject of other studies underway at NIST. Generation and use are referenced frequently here but are not examined in as much detail.

## 1. EFFICIENCY, RELIABILITY, AND STABILITY

Despite the increased use of electricity over the past decade, the utilities have not had to increase installed power-generation capacity significantly to meet the demand [14]. However, a significant number of independent (non-utility) power producers have emerged and have been granted access to the transmission system by order of the Federal Electricity Regulatory Board (FERC). Current power-generation capacity appears adequate for the near future at least [14]. This situation contrasts with the predictions of a decade ago, which warned of significant shortages of electricity. Further, the present growth in demand is being met without significant construction of new transmission systems, either. This state of affairs results from improving the efficiency of existing power systems. There are many additional opportunities for improvements to power systems, affecting not just efficiency, but also reliability and stability. Exploiting these opportunities, however, is highly dependent on the continued adoption of new technology. These opportunities arise in the transmission and distribution,

**Figure 1: MAPPING DRIVING FORCES INTO TECHNICAL NEEDS AND SOLUTIONS**




generation, and use of electricity, and in component reliability more generally. All are discussed in the following sections.

## 1.1 Transmission and Distribution Efficiency

Some technical background will prove useful in understanding the following discussion of transmission and distribution systems. If concepts such as impedance, reactive power, and active power are already familiar to you, you may wish to skip ahead to Section 1.1.1.

The flow of electric power in transmission and distribution systems is governed by physical laws and often not by design. The path that an alternating current takes through a power system is determined by the system's *operating parameters*. These parameters are determined by the network configuration and the loading of the system. The three most important operating parameters are: voltage, which is the pressure causing electricity to move; impedance, which is so named because it impedes the flow of electricity; and power factor, which reflects the relative timing of the varying level of voltage compared to a varying level of current at a specific point in the system. Power factor also reflects the breakdown of electric power into *active power* and *reactive power*, which will be discussed further below.

The power-handling capacity of a transmission system is limited. Principal among the limiting factors are impedance and stability. The impedance of the transmission system has two components:

resistance and reactance. Both can impede the flow of electricity, but only resistance leads to heating. Heating is caused by the dissipation of power. Resistance, and thus heating, arises from multiple sources, such as: the electrical resistance of the wires in the system, including those in power-system equipment; the magnetic properties of the cores in power transformers and inductors; and the insulating (or dielectric) properties of the materials in capacitors. The amount of heating that a transmission system can tolerate is referred to as its *thermal limit*. Above that limit, equipment in the system begins breaking down. The thermal limit is sometimes said to be the *ultimate limit* to the capacity of a transmission system because it is so hard to reduce thermal effects. Reactance arises from different properties of power-system equipment. It is sourced in the inductance (the ability to store magnetic energy) and in the capacitance (the ability to store electric energy) of the equipment. All power-system equipment exhibits these properties to varying degrees. For example, the long wires used in a transmission line not only exhibit resistance but also exhibit both inductance and capacitance.

In addition to impedance, electrical instabilities can limit the power-handling capacity of a transmission system. Instabilities can arise because the power flow in a transmission system evolves in time. Power flow can behave much like waves in a swimming pool. Major amounts of power can travel back and forth in a power system, just like waves bouncing off the sides of the pool. These waves of electricity are stimulated by changing levels of electric power put into, and drawn from, various parts of the transmission system by switching actions and by changes in demand for electricity. The waves alternately fill and empty the so-called *reactive* energy storage areas associated with system inductances and capacitances. For this reason, the power flow that these waves represent is called *reactive power*. These inductances and capacitances occur in components intentionally designed to exhibit these properties (that is, in inductors and capacitors) or inadvertantly in other components, such as the wires in transmission lines. Unfortunately, the waves of reactive power utilize system capacity. As they move, they create heating, without delivering useful electricity to end users. Thus, the level of electric power actually delivered to end users must be reduced to provide enough thermal capacity in the transmission system to accommodate the waves of reactive power. [Note that the industry calls inductors *reactors*, even though *both* inductors *and* capacitors exhibit reactance.]

To increase the power-handling capacity of a transmission line, it is necessary to decrease the flow of reactive power, increase the flow of non-reactive power, or *active power*, and maintain system stability while doing so. It is this active power that actually performs services for the end users. Also, it is desirable to decrease any resistances in order to decrease the losses attributable to resistance for both reactive and active power. Currently, transmission and distribution losses account for about 7 percent of the electricity generated in the United States [42].

The next two sections describe technologies that can help achieve these aims. First, power-electronic devices can help reduce the flow of reactive power, while improving system stability and reliability as well. Superconductors have the potential to reduce resistive losses, but may also help with system stability and reliability. And, finally, real-time network control can improve system stability. It can stabilize the network through control of power-electronic devices and the end-users demand for electric power.

### 1.1.1 Power-electronic devices

At present, system parameters in transmission and distribution systems are not controlled well enough to channel the flow of power across specific paths in the most efficient way. For example, the mechanical switching of circuits and of *compensation* components, such as capacitor banks, is relatively slow. Voltage disturbances due to unavoidable events, such as lightning strikes and equipment failures, cannot generally be controlled fast enough to prevent their propagation through power systems. Because of these control problems, the capacity of some transmission lines to carry electric power is limited by system stability and not by the inherent limits at which overheating and subsequent failure of the power equipment occurs. Deregulation is changing the utilities' operating environment, not just its economic environment; and the need for better control of power flow is becoming critically important as a result [14].

Power-flow controllers, based on electronic devices, are being developed to give operators a previously unavailable level of control over transmission system parameters in order to maintain stability. The controllers also enable compensating for, that is, reducing the reactive part of the impedance. When stability is improved, or when the reactive part of impedance is reduced, the power flowing through a transmission system to end users can be increased to approach more closely the thermal limits imposed by the resistive part of the impedance. By increasing the power transfer capability of existing transmission systems in this way, the utilities avoid the cost of construction of new power lines [68].

The utilities are now moving toward implementation of power-flow-control technologies to meet the technical needs for improved efficiency and stability of power systems. A long transmission line connecting, for example, a remote power plant to a distribution center, has an impedance which limits its power-handling capacity. In the past, the straightforward technical solution was to build additional transmission lines in parallel to provide additional capacity. But this solution has three major problems: high cost; long lead times; and the almost insurmountable problems of obtaining additional rights-of-way, particularly in urban areas where the demand is increasing at the highest rate. Utilities have traditionally used capacitors and shunt reactors (inductors) switched into and out of networks with mechanical switches to compensate for the reactance of the lines and changing load impedances. In contrast, power-electronics-based technologies are now being developed that control transmission line impedance. This approach should greatly increase efficiencies for electric-power delivery. With better control over operating-system impedances that these new approaches provide, the amount of electric power transferable over transmission lines will increase because the lines can be operated closer to their thermal limits. These same power-flow-control technologies, along with more customized approaches, can also be used for maintaining high power quality since poor power quality arises from a lack of control over the system operating parameters.

One system for power-flow control employing the above approaches has been developed by EPRI and is called the *flexible ac transmission system* or FACTS [14]. FACTS technology is presently being tested prior to widespread use. For example, the Bonneville Power Administration (BPA) has just tested a FACTS system on a 500 kilovolt transmission line with 2500 megawatts of capacity [69]. The successful completion of this test has led BPA to anticipate that FACTS technology could save them $150 million over the next 20 years. Application of FACTS technology to large systems will require that new automated systems support wide-area real-time control, possibly employing satellites, to assure stability, especially in the face of increased numbers of independent power producers. In addition, more advanced techniques will likely be needed to decrease the sensitivity of the power network to frequency mismatches.

Over the past 15 years, a number of new FACTS devices have emerged with important capabilities. The first of these devices switched large external capacitor banks in series with, or across (shunt), transmission lines. The new element was the use of electrical devices, called thyristors, to do the switching, rather than mechanical switches [70]. The thyristors provided much faster switching capability.

> One example of these devices is the static var compensator (SVC), which is simply a shunt capacitor bank. The SVC provides voltage support near heavy loads at the end of a transmission line, but does not control power flow.

> Another example is the thyristor-controlled series capacitor (TCSC), which places a capacitor bank in series with a transmission line. It dampens disturbances on the line through control of the line impedance. The TCSC enables the line to operate closer to its thermal limits and thus enables increased power flows over long distances. The Western Area Power Administration (WAPA) installed a TCSC in 1992 and increased the power handling capability of one line considerably, from 300 to 400 megawatts [68].

Thereafter, newer FACTS devices were implemented that eliminated the need for large external circuit elements [large capacitors and reactors (inductors)] by using gate turn-off thyristors (GTOs) to simulate these elements electronically. They further reduced the cost of the controllers and improved performance, too.

> One example of these newer FACTS devices is the static compensator (STATCOM), or equivalently, the static condenser (STATCON). The STATCOM provides voltage support by generating or absorbing reactive power through an electronic shunt connection that can quickly dampen major power-system disturbances. The STATCOM is actually a power-electronics system having dc storage, a converter, and a transformer to hold a power line at the required voltage level by supplying, or absorbing, reactive power. Depending on the size of the energy storage, it can supply real power to the load for short periods. EPRI and the Tennessee Valley Authority (TVA) have demonstrated a 100 million volt ampere reactive STATCOM that eliminated the need for construction of an additional 161 kilovolt transmission line into the Johnson City, Tennessee area. TVA's cost was $10 million for the FACTS versus $20 million for just the new transformer bank required by the proposed transmission line 14].

> Another example of the newer FACTS devices is the Unified Power Flow Controller (UPFC). It is so named because it provides control over all three power-flow parameters of voltage, line impedance, and power factor, in one device. This device is being tested in the Inez Substation of American Electric Power in eastern Kentucky.

Although much of the technology for FACTS is presently available, there are still technical challenges to be addressed. There is a need for low-cost, accurate sensors that can be installed throughout the transmission systems to monitor power-system disturbances. There is an accompanying need for communication systems to monitor the sensors and to coordinate the operation of the FACTS devices.

#### 1.1.2 High-temperature superconductors

One possible route to loss reduction is being pursued through the development of superconducting electric-power equipment [71]. This approach attacks principally the resistive losses.

Although much of existing power equipment is highly efficient, there is room for improvement in generators, cables, and transformers, where the electrical resistance of the conductors produces power losses. In the 1960s and 1970s, there was a major effort to develop transformers and cables having low-temperature superconductors as elements, to minimize power losses. Because of the high cost of refrigeration required to maintain the low-temperature superconductors at liquid-helium temperatures (1.8 K to 4.2 K), the equipment was not cost-effective, even when evaluated on a life-cycle cost basis; and the development efforts ended in the early 1980s. The recent development of high-temperature superconductors, which are significantly less expensive to refrigerate, has renewed interest in superconducting power equipment. This interest has resulted in worldwide development of superconducting cables, generators, and transformers [71]. Additionally, further incentive to improve efficiencies of power equipment has been provided by the National Energy Policy Act (NEPA) of 1992, which mandates that the U.S. Department of Energy assess regulations governing the efficiencies of transformers and motors.

High-temperature superconductors, which become superconducting at liquid-nitrogen temperatures (77K), were discovered in 1987 and have the primary advantage that refrigeration technology can maintain temperatures at or below 77K without great expense and inconvenience. However, the high-temperature superconductors are all ceramics, which are difficult to fabricate into the wires and tapes that are necessary for electric-power equipment. The first high-temperature superconductor devices developed were fault-current limiters (FCLs) that limit the amplitude of large currents due to short circuits induced by lightning strikes. These devices were attractive as an early application of high-temperature superconductors because they utilized bulk ceramic material that was easier to fabricate than the high-amperage wire or tape conductor required for other power equipment. The application of high-temperature superconductors to transformers, cables, and generators is also under development. The present state of development for the major applications of high-temperature superconductors is described below. The technical needs are similar for all FCL applications and are discussed at the end of this section.

**Fault-current limiters (FCLs):** Fault currents can destabilize the power grid over a large area. Conventional devices used to limit fault currents include series resistors and reactors (inductors), but these introduce significant power losses and voltage drops during normal operation. High-temperature-superconductor FCLs do not have these inherent disadvantages. A consortium formed under the Department of Energy's (DOE's) Superconductor Partnership Initiative, comprising Lockheed Martin, Southern California Edison, Los Alamos National Laboratory, and the American Superconducting Corporation, has developed laboratory prototype FCLs rated for 480 volts and 1 kiloampere, and for 2.4 kilovolts and 3.1 kiloamperes [72]. These FCLs use power electronics to switch a superconducting reactor into the circuit under fault conditions in order to limit the current in less than one cycle. The current limiting capability of the superconducting FCLs eliminates or at least delays the need to upgrade power equipment such as circuit breakers, buses, disconnect switches. As more non-utility generators (NUGS) come on line and as electricity usage increases, the power-system equipment must be able to handle increasing amounts of power during normal operation and larger currents in the event of a fault. Installing FCLs eliminates the need for upgrading equipment such as circuit breakers because they maintain currents within the existing equipment's specified short-circuit duty.

**Transformers:** Conventional transformers of the largest sizes are highly efficient; power losses are less than 1 percent of their nominal power rating when operating at full rated load, and the losses are lower at reduced loads. However, when considered over the life of the transformer, the cost of the losses can match the initial capital investment in the transformer. High-temperature-superconductor designs can potentially improve efficiencies while reducing the volume and weight of transformers relative to conventional designs. Additionally, unlike conventional power transformers, high-temperature-superconductor transformers use no substantial amounts of materials that present either fire or environmental hazards. The national savings to be realized from high-temperature superconductor transformers has been estimated to be about $25 billion through the year 2030 [73]. ABB, American Superconductor Corporation, Electricité de France, Services Industriels de Geneve, DOE, and the Swiss Utilities Study Fund are jointly building a three-phase, 630 kilovolt ampere, 50 hertz, high-temperature-superconductor transformer to be demonstrated in 1997. Rochester Gas and Electric, Oak Ridge National Laboratories, the Waukesha Division of General Signal Corporation, and Intermagnetics General Corporation are building a 1 megavolt ampere high-temperature-superconductor demonstration unit that is now in the design phase [74]. Further, a single-phase, 13.8 kilovolt transformer, sized as one leg of a 138 kilovolt, 30 megavolt-ampere unit initially operating at ten percent of the rated voltage, is to be built by the summer of 1997, and tested in the fall to serve as a test bed for cryogenic systems and conductors.

**Cables:** The present rate of installation of new underground transmission circuits in the U.S. utility network is about 100 miles annually. This rate of installation can be expected to increase as transmission needs rise in populated areas. Many of the underground cable installations are installed in pipes; about 20 percent of these have exceeded their nominal life of 40 years. High-temperature superconductor cables are attractive replacements for existing underground cables because they can increase the ampacity [75] as much as 350 percent for certain designs [76]. These cables can even exceed overhead line ampacity in some cases and can eliminate the need for double and triple cable circuits by meeting the highest current requirements. Pirelli Cable Company has demonstrated a high-temperature-superconductor conductor that exceeded its anticipated performance and is developing a room-temperature-dielectric (RTD) cable where only the center conductor is maintained at cryogenic temperatures.

**Motors and generators:** A 29 horsepower, air-core, synchronous motor with a rotating, high-temperature superconductor field winding cooled to 27 K by helium gas has been demonstrated [77]. There is a problem in that power equipment with high inherent self-fields, such as motors and transformers, require either improvements in the superconducting tape used or operation at reduced temperatures.

There are three significant technical needs to be addressed in the development of high-temperature-superconductor power equipment. First, the performance of the electrical insulation under cryogenic conditions must be confirmed. Second, the ac power-transfer efficiencies must be accurately measured. Although high-temperature superconductors have zero dc resistance when in the superconducting state, they do experience ac power losses, which, although small, need to be quantified. It will be a metrological challenge to measure the small power losses of these high efficiency devices. Third, the operation of the high-temperature superconductors under fault-current conditions must be investigated. For the device to be of practical use in many applications, it must remain superconducting, or it must recover quickly enough under fault-current conditions to permit automatic reclosure of circuit breakers.

## 1.2 Transmission and Distribution Stability Through Real-Time Control

Real-time control of power networks will be needed to maintain the stability of transmission and distributions systems while improving power-transfer efficiencies. Such control is particularly important as electric-power consumption rises and as the wheeling of electric power increases with deregulation. In order to implement such control, the utilities will have to install many more sensors than are presently installed, reduce the peak loads through better control of their customers' demands, and employ advanced communications and control techniques, such as the use of artificial-intelligence approaches. The technical needs arising from real-time control are discussed in the following subsections.

### 1.2.1 Cost-effective sensors

Sensors are used throughout the electric-power system in the generation, transmission, and distribution segments for limited monitoring of power-system equipment. However, as attempts to control the operating parameters of power networks increases, the installation of many more sensors will likely be needed to monitor system disturbances.

Sensors in the transmission and distribution systems are needed in greater numbers to measure voltage, current, and power factor. The additional measurements will provide more information on the state of the system so that proper operation of end-user equipment can be ensured. The availability of inexpensive sensors having no violent failure modes and not requiring periodic recalibration could lead to major improvements in the observability of power-system irregularities [78]. Such capability would have found critical application in the massive power outages in the western United States on July 3, 1996 and August 10, 1997. Significantly improved diagnostic coverage of the system could perhaps have provided advance warning of the problems and would have been useful in determining the causes of the outages [79].

Sensors are also important for measurements of power quality, as discussed further in Section 4 of this chapter. The sensors can help quantify harmonics of the fundamental power-frequency voltage and current, voltage dips, spikes, and other transients; and the sensors can help identify the sources of power quality degradation to protect customer equipment. Another important function of sensors is the detection of high-impedance faults. These faults can occur when downed power lines do not draw enough current to trip protective equipment, and can result in lost lives and significant damage from fires.

Distribution systems are virtually unmonitored for three historical reasons: (1) the utilities' lack of processing capability for large quantities of data, (2) the high cost of communicating field data to control centers, and (3) the prohibitive cost of sensors and their installation, which is typically $5,000 for a common three-phase site. The decreasing cost and increasing computing power of personal computers and workstations allows the utilities to address the first need in cost-effective ways with existing technologies. Developing technologies such as digital cellular communications and low-earth-orbit satellite (LEOS) telephony will make the second need of communicating field data addressable in the near future. The need for low-cost sensors in the field presents greater technical challenges that require further research and development. Although there are low-cost sensors presently available that meet the measurement requirements, they typically do not meet the additional requirements for field installations: (1) a long maintenance-free life of from 5 to 10 years; (2) self-powered or inductively powered; (3) simple installation; and (4) self-calibrating or remotely calibratable. Sensors are required to have measurement uncertainties of less than 1 percent for system monitoring and from 5 to 10 percent for diagnostics and condition monitoring [80]. However, the required uncertainties and other needs are poorly understood for distribution systems since historically they have been sparsely monitored. These needs will become more clearly defined as more custom power devices are brought on line and as the interactions among them in service become better understood.

There also exists a need in bulk-power transmission systems, for protection, monitoring, and metering. There is a need both for primary sensors that measure voltage and current and for secondary sensors (meters) that compute other quantities such as power, energy, and frequency from the measurements made by the primary sensors.

There is a definite need for the calibration of primary sensors in service. It is desirable that new sensors be self-calibrating, remotely calibratable, or have characteristics that change over time in a predictable manner since the alternative of calibrating sensors in the field is so costly. There is also a need to determine the quality of sensors presently installed.

Frequency is one quantity monitored by sensors for relay systems designed to protect generating plants. Capacitively-coupled voltage transformers (CCVTs) are often used for voltage measurement and frequency monitoring in relay applications, but some CCVTs have problems in determining 60 Hz voltage magnitude with sufficient accuracy. They may also cause errors in the frequency measurements used by protective relays. When a power disturbance occurs that results in a significant interruption of power flow, the demand of the load for electrical power may exceed generating capacity, resulting in a drop in both voltage and frequency of the power system. At the generation end, these changes may result in overheating of the generators as attempts are made to produce more power. Also, the turbines that drive the generators are designed to operate within a narrow range of rotational frequency and if operated outside the limits of this range may suffer mechanical damage. Some CCVTs have a transient response to a sudden system voltage drop that may occur at a frequency that differs from the power system frequency. Since this effect may lead to a faulty trigger of a relay that removes some load in an effort to help restore the frequency and voltage, there is a need to improve the frequency measurements. There are also problems in accurately measuring harmonics where the tuning inductance of the CCVT destroys its frequency response. Another need exists for combining CCVTs and current transformers (CTs) into a single package.

Some utilities desire new sensing techniques for determining power flow and imbalances in the power system. There is a need for measurements in power systems to be referenced with a common time tag to obtain better information about how power is flowing at any given time. Remote sensing for monitoring of power systems makes primary sensors, timing, and communication systems of overriding importance, and requires the development of techniques for synchronized phasor measurements.

Optical sensors represent one possible solution to the need for reliable, economical sensors. Conventional sensors for voltage and current are expensive and require large volumes of electrical insulation when used on high-voltage lines. Current transformers (CTs) installed on 500 kilovolt power lines have exploded when they fail because of the flammability of the insulating oil used within them [81]. Several manufacturers, including ABB, 3M, and Square D [81, 82, 83], have developed optical current transducers (OCTs) that are designed with all solid insulating materials and are therefore intrinsically safe. These OCTs utilize the magneto-optic Faraday effect in either optical crystals or fibers to induce a rotation in the plane of polarization of a light beam passed through the sensor head. The rotational change is linearly proportional to the current through the sensor. OCTs have the additional advantages of immunity to electromagnetic interference and wide dynamic range. Although saturation is not a problem, as with iron-core current transformers, the OCTs are linear over only a finite current range. This does not limit the usefulness of OCTs since their linear range is selected by appropriate sensor-head design and since measurements of currents outside of their linear range are readily corrected by more complex signal-processing techniques. The wide bandwidth of the OCTs, limited only by the optical detector, makes them applicable for both power-frequency metering and measurements of transient currents.

OCTs are presently being field-tested in the TVA system as well as elsewhere [81, 82] and preliminary results indicate that they satisfy requirements for metering-class measurement uncertainty.

Optical voltage sensors are also under development as replacements for voltage transformers (VTs). They have the same advantages as the optical OCTs and are anticipated to be lower in cost than conventional CTs and VTs when mass-produced. They may become the low-cost, general-purpose voltage and current sensors devices desired by utilities. Questions remain about their stability, sensitivity, and linearity; and these questions must be addressed before these sensors are embraced by the utilities on a wide scale. The sensitivity of the optical sensors to vibration and temperature changes must be minimized by either design or signal processing. The long-term stability of these sensors is under study in field trials, but techniques for calibrating them in the field and in the test laboratory must yet be developed.

### 1.2.2 Demand-side management

As mentioned in Section 1.2.4 of Chapter One, demand-side management (DSM) programs are becoming increasingly popular with the utilities to reduce the level of demand and the fluctuation in demand. The purpose is to mitigate the need for construction of new electrical generation and transmission systems. The most common type of DSM program promotes the use of energy-efficient lighting, motors, etc. by electricity consumers. The technical needs associated with this type of program are primarily related to the development and characterization of energy-efficient devices, which were discussed in Section 1.4 of this chapter.

The other type of DSM program involves the direct real-time involvement of the utility, either by granting the utility some control over electrical devices used by the consumer (such as in Pepco's Kilowatcher Club), or by instituting real-time pricing. With real-time pricing the consumers are continuously informed of the instantaneous cost of electricity, and can adjust their use patterns accordingly. The technical barriers to these types of programs are primarily related to information-system integration. The three primary barriers are: (1) unavailability of a viable, unified, standard communication architecture that extends from the customer's meter or field device to the utility; (2) lack of harmonization of controlling software, thus promoting proprietary systems for each utility that limit the amount of information that can be shared with other companies and that raise software costs; and (3) deployment of viable, affordable communication systems.

### 1.2.3 Artificial intelligence

The eastern U.S./Canadian interconnected power system is often modeled with 2000 generators. To model this system mathematically and describe its dynamics requires up to 20,000 first order differential equations [84]. Although the system is non-linear, the linear approximation to its behavior works well. However, due to the sheer complexity of the system, the process of modeling and analysis is clearly a job for computers, even when the governing equations are linearized. The non-linearity of the interconnected power system is seen by the suddenness of the onset of oscillatory behavior. There may be no indication of a problem as power flow over a system intertie is increased. Then, suddenly, a certain stability limit is reached beyond which a slight increase in power flow causes oscillations. These oscillations increase quickly in amplitude. All this can occur without the need for a system fault to start the process.

Deregulation of the utilities will promote more bulk-power wheeling and possibly more retail wheeling, with greater power transfer across system interties along with the anticipated increase in system monitoring with many more sensors than are presently in use. This change will give rise to the need for computer monitoring, analysis, and control. An increase in applications of artificial intelligence (AI) techniques, such as fuzzy logic, neural networks, and expert systems, will likely be desired by the electric-power industry, as an already complex system becomes even more sophisticated. Similarly, applications of AI techniques will be needed for monitoring of electric-power equipment. One area of application of AI techniques already being investigated is partial-discharge measurements [85, 86].

### 1.2.4 Communications and control

In the Fall of 1989, the Department of Energy's (DOE's) Office of Energy Storage and Distribution, together with the Bonneville Power Administration (BPA) and the Western Area Power Administration (WAPA), came together to assess related R&D needs for future electric-power-system operation. One of the major areas for the resulting Joint DOE/BPA/WAPA Research Initiatives was real-time control and operation [87]. As a result, the Western System Dynamic Information Network (WesDINet) was planned in response to the utilities' needs for direct information about system characteristics, accuracy of system models, and operational performance [88].

Existing system monitors and communications do not provide the comprehensive data access and real-time integration necessary to control fully the wide areas of the power system. A wide-area measurement system (WAMS) for real-time control and operation of electric-power systems is under development [88]. It will provide the key technologies for WesDINet, such as the mathematical software for extracting information from measurements. The communication links will provide high-performance support for sharing of reference signals for wide-area correlation, automatic posting of disturbance directories on computer bulletin boards, exchanges of data records, and interactive assistance in measurement operations and analysis from remote locations.

Replacement of present point-to-point analog communications in power systems with digital channels having comparable bandwidth and resolution could prove to be a poor investment. There is a need for new communication system architectures having the flexibility to accommodate developments in digital technologies in order to replace analog communications with digital systems in the most cost-effective manner [89].

There is also a need for real-time assessment of actual power flows and dynamic capacity, and better control of power flow across interties. In the WAPA system, a persistent constraint is inadvertent *loop flows* that readily consume all available transmission capacity and that limit the capacity of several transmission lines [90]. Phase-shifting transformers and advanced series compensation devices may be used to relieve loop flows.

For the automation of distribution-system control, information systems are needed to manage field equipment from the substation to the meter. Four tools are being developed by four different utilities' departments to address the needs for automated distribution systems [91]: (1) automated mapping and facilities management systems, developed by engineering departments; (2) supervisory control and data acquisition systems (SCADA) developed by operating departments; (3) load-management systems developed by power supply departments; and (4) automated meter-reading systems developed by business departments. Although the four tools often rely on common techniques, they are not often integrated. There are several barriers to such information-system integration. First, as mentioned above, there is no viable and unified communications architecture presently available that extends from the meter or field device through the utility office local area network (LAN). Second, the database or facility-management component of utility mapping systems is not easily adapted to real-time data. This component often lacks external program links, depends on operator, rather than event-driven, initiation, and does not support structured query language (SQL) standards. Third, the user interface lacks display, or detail responsiveness, needed for system operations. SCADA interfaces are traditionally oversimplified representations of distribution systems and have had difficulty keeping up with general user-interface options available from leading computer operating systems. Fourth, the utility industry, and particularly the electric-utility segment, considers its needs unique. Utility vendors have, as a result, provided proprietary systems with communications protocols and computer bus architectures that limit the sharing of technology with other industries and raise costs. Fifth, most integration efforts to date have involved custom engineering and programming. Sixth, vendors have been product-driven rather than design-driven. That is they sell communications systems within the utilities' traditional organizational structure rather designing for the overall system. Vendors have been reluctant to participate in multi-vendor teams to meet utilities needs. Finally, there is a need for standardization of communications-system protocols to allow utilities to implement distribution-system automation.

## 1.3 Generation Efficiency

Inefficiencies, or power losses, can also occur at the generation end of the power system, where there is also a need for improved measurement capability. Principal among these is the need for improved measurement of temperature in coal-fire boilers. These boilers are used to generate the steam that powers the turbines used for generating nearly 60 percent of the electricity used in the United States. Temperatures even slightly too high can significantly reduce boiler lifetimes. Temperatures even slightly too low will reduce efficiency.

Also, existing power-plant meters that measure flow in steam and water pipes can become fouled, resulting in inaccurate measurements. In particular, water in power plants is injected into steam to control steam temperature. Improved measurement accuracy for water flow can lead to a variety of benefits for reasons similar to those noted for temperature measurement above. One of the benefits is improved system lifetime because improved control of water flow provides improved control of temperature. Improved control of temperature, in turn, reduces thermal cycling and unintended operation at too high a temperature, both of which can shorten system lifetime. Another benefit is improved efficiency. Unintended operation at too low a temperature reduces system efficiency. For example, a one percent error in flow measurement can translate into a one percent increase in fuel consumption. A third benefit is greater power output. Improved temperature control enables operating closer to the legal limits specified for every power plant, without the risk of exceeding those limits. EPRI and NIST have recently begun work under a cooperative research and development agreement (CRADA) to employ a noninvasive acoustic technique for measuring water flow in pipes. This technique will avoid the fouling problem encountered with conventional flow sensors. This technique also enables making flow measurements conveniently in more locations within a power plant, for improved overall characterization of the generation process.

## 1.4 End-Use Efficiency

Reduction in wasted electrical power can be effected through the development of end-use equipment with improved electrical efficiencies. Efforts are underway to develop energy-efficient technologies for lighting, motors, and heating; areas that represent the vast majority of electrical power consumption. In addition to development efforts for superconducting motors described above, the 1992 Energy Policy Act [92] has initiated a study to develop a series of tests to ensure the efficiencies of electric motors, which use approximately 60 percent of the electricity generated in the United States [93].

### 1.4.1 Lighting

Substantial savings in electricity consumption can be obtained by the use of efficient lighting devices (e.g., fluorescent lights versus incandescent lights), and this is a common demand-side management process utilized by utilities to reduce power demands. However, it has been pointed out that the present efficiency of lighting has not substantially increased in the last 15 to 20 years [94], even though the most efficient light sources available today are well below theoretical maximums. What the lighting industry would like to develop is a *white* lamp with an efficiency of about 200 lumens/watt (about twice that available today), but many researchers are of the opinion that this will require a *breakthrough* development [94].

Pursuing such a breakthrough requires addressing an enormously complex multi-disciplinary problem which would require research in many areas, including electrical discharges, light emission, advanced materials, electric-power devices, aging phenomena, etc. Specific technical needs fall into two main areas: (1) materials, such as better emitters, phosphors, electrodes, envelopes, seals, and glasses; and (2) discharge chemistry and physics, such as the determination of fundamental data on thermochemistry, electron and ion diffusion and collisions, collisional broadening of spectral lines, molecular radiation, optical emission, surface interactions, and reaction rates. The development of new materials and the measurement of fundamental data represent the first step towards development of the next generation of lighting.

### 1.4.2 Motors

Efforts are being made to improve the efficiencies of electric motors in end-use applications. The 1992 National Energy Policy Act [92] called for the development of test procedures and certification requirements for certain commercial motors. Efficiency standards are now being developed for general-purpose, polyphase induction motors with power ratings from 1 horsepower to 200 horsepower. The proposed rules have been reviewed by the Department of Energy and released [95].

The development of motors using high-temperature-superconductor technology for applications where the benefits of reduced size and losses outweigh the added expense and complexity of the high-temperature-superconductor design has been discussed in Section 1.1.2. Improvement in ac-induction-motor efficiencies is also being realized through the use of variable-speed controllers, also known as adjustable speed drives (ASDs). Formerly, motors were operated at constant speed; and flow was regulated with a throttle or bypass. The variable-speed drive rectifies the line power and uses an inverter to control the motor speed by varying the frequency of the power to the motor. Microprocessor-based controllers and pulse-width modulation techniques are also being developed. The use of these electronic controllers will result in a much more energy-efficient way of controlling motors, but these controllers will also have some disadvantages. The harmonics introduced into the power lines by the controller can affect revenue meters and may be incompatible with other sensitive equipment connected to the same lines. The effects of harmonics are discussed in Section 4.2. Additionally, the harmonics generated by the controller may also increase eddy currents in the motor itself, leading to elevated temperatures that reduce the motor lifetime and reliability.

EPRI has a targeted research project to develop high-performance motors through the improvement of motor materials, circuits, controls, and components [96]. The project is intended to incorporate improved technology into motors that will offer higher efficiencies, higher power capabilities, and possibly lower costs. Additional concepts of high-speed motors, high-temperature superconductor motors, and advanced insulation designs are to be explored.

### 1.4.3 Heating

Steady increases in heat-pump efficiencies have led to a 27 percent increase in the seasonal energy-efficiency ratio (SEER) ratings of air-source heat pumps over the last decade [97], making heat pumps more attractive than earlier, in terms of energy costs. New designs are being developed to serve both space heating and water heating needs with resulting energy cost savings of 20 percent to 40 percent over separate units. Improved designs, such as in ground-source heat pumps (GSHP), now extend their applicability to climates in regions further north. The dual-fuel heat pump (DFHP) combines a gas furnace with a heat pump to enable the most efficient operation, depending on temperature, as either a heat pump, gas furnace, or combination of the two.

In addition to the efficiency improvements, advances in environmental compatibility have also been made. EPRI together with NIST and others have accelerated the development of zero-ozone-depletion-potential (Zero-ODP) refrigerants to make heat pumps environmentally safe.

## 1.5 Component Reliability

Power-system reliability is enhanced through the reduction of equipment failures. The failures can be reduced through predictive maintenance using advanced equipment monitoring technologies, and in particular, through more accurate on-line condition monitoring. The improved reliability of power-system components results in the prevention of lost revenue by reducing power outages. Additional cost savings for utilities can be realized by extending the usable lifetime of expensive equipment, such as power transformers, beyond their design lifetimes, which delays the outlay of capital for replacing old equipment.

### 1.5.1 Reliability testing

Since lightning is a major cause of power-system disturbances, electrical-power equipment is subjected to testing with high-voltage impulses before being placed in service to ensure reliability. International standards governing testing with lightning impulses have been recently revised. They introduce the *reference measurement system* that is used for comparative testing of impulse voltage dividers that are used in routine testing [98, 99]. The reference systems are required to have lower measurement uncertainties than those used for routine tests. There is a technical need to ensure that the more stringent requirements placed upon reference systems are met.

### 1.5.2 Condition monitoring

A recent development in the area of maintenance of power equipment is a change from the *corrective maintenance* approach or the *time-scheduled maintenance* approach to a *reliability-centered maintenance*, or RCM, approach. This change is expected to reduce maintenance costs by 25 percent to 50 percent.

Many utilities use the corrective-maintenance approach on substation equipment, which is essentially the approach of waiting until a component fails before replacing it. In the past, this approach has proven to be cost-effective. In power plants and for other components in power systems, maintenance has traditionally been based on a time-scheduled replacement or refurbishment of equipment. This is very costly because it is based on the manufacturers' conservative recommendations. As power systems become more complex with more sophisticated equipment being installed, the RCM approach is being implemented. RCM, which was developed by the airline industry to make jumbo jets economical, relies on component condition and criticality, in lieu of routine scheduling for inspection and overhauling. Those components identified as critical are replaced on the conservative time-scheduled basis, while others are replaced on a conditional basis. RCM was first implemented in the electric-power industry for nuclear plants and is now being extended to substations. Condition-monitoring information obtained from diagnostic sensors is essential to these maintenance programs.

Many sensors are now being developed to monitor the conditions of transformers, generators, and other power equipment. Among these are thermography scans to detect hot spots due to abnormally high current flows, winding resistance tests to detect failing connections, and capacitance of winding insulation to determine aging or the presence of moisture. As reported by EPRI [14], a thermography scan detected a faulty bushing on a nuclear power plant's main step-up transformer, and averted an imminent failure, saving an estimated $4.8 million in lost electricity production.

Internal transformer monitoring is also needed and is being made possible by the development of in-situ semiconductor gas sensors [100]. Gas evolution in power transformers has been used as a diagnostic tool to monitor hot-spot temperature and partial-discharge activity in power transformers [101]. Gas-in-oil analysis is routinely performed on oil samples taken from power transformers to assess the condition of the unit. Now a real-time semiconductor monitor has been demonstrated which detects four key gases: hydrogen, acetylene, ethylene, and carbon monoxide. They are detected by the voltage produced when they adhere to a catalytic metal surface in a metal-insulator-semiconductor structure. Four sensors, each sensitive to a different gas, are combined in a single unit inserted directly into the transformer oil. These sensors provide an accurate time profile of changes and trends in dissolved gas concentrations in the general range of 20 ppm to 2000 ppm with uncertainties of ±10 percent or less. The sensors, which are insensitive to water, methane, ethane, carbon dioxide, nitrogen, and mineral oil, are intended to eliminate the need for routine dissolved-gas analysis (DGA).

Another example of a recently-developed condition monitor is a fiber-optic strain gauge developed to monitor corrosion in stainless steel steam generator tubes [102]. A significant problem in nuclear steam generators is intergranular attack (IGA) and surface corrosion cracking (SCC) in Alloy 600 tubing, which can result in failure of the tubes. Because water is flowing at 1 $m^3/s$ (35 $ft^3/s$) at 7.6 MPa (1100 psi), and 316 °C (600 °F), conventional strain gauges cannot survive; and interferometric techniques are unsuitable for long-term observation due to changes in tube surface, turbulence in intervening air, etc. A fiber-optic strain gauge was recently demonstrated that is capable of detecting the onset of IGA/SCC earlier than conventional gauges and of indicating progression of IGA/SCC even though the eventual failure was not directly under the gauge.

Analogous to gas-in-oil monitoring of power transformers, EPRI has a research and development program to use by-products in $SF_6$-insulated equipment to monitor their internal condition [103]. A database is presently being established. It is based on gas-chromatographic analyses of by-products in samples taken from circuit breakers in service. The database is being established at an accelerated pace compared to the gas-in-oil database for power transformers. The gas-in-oil database was assembled over a twenty-year period. The study intends to identify key concentration levels of $SF_6$ contaminants so that informed judgements can be made before opening equipment for inspection and maintenance. There is a need to minimize the opening of gas-insulated equipment and the potential venting of $SF_6$ to the atmosphere, as discussed below in Section 3.1.1.

**Partial-discharge monitoring:** The detection and quantification of partial discharges (PDs) has become important in assessing the integrity and remaining life of electrical insulation and in certifying the performance of high-voltage electric-power apparatus. There has also been increasing interest by the electrical manufacturers and power utilities in the use of on-line PD monitoring as a diagnostic for locating incipient faults in cables [104], transformers [105], and rotating machinery [106]. The Nuclear Regulatory Commission is exploring possibilities of adding in-situ PD testing of instrument cables to the list of measurements required for approving nuclear-power-plant life extension [107]. The measurement of PD is also important in evaluating the performance of electronic instrumentation and components.

Partial discharge is a localized discharge phenomenon that is usually impulsive and often occurs at defect sites such as voids and cracks in electrical insulation where there can be significant local enhancements in electric-field strength [108]. It is known that the occurrence of PD can lead to rapid aging of all types of insulating materials including gaseous, liquid, and solid insulation. It is also known that PD is often a precursor to complete electrical breakdown that may result in catastrophic failure of equipment. Additionally, it can be a source of impulsive electrical and radiative noise that may adversely affect power quality and interfere with radio communications and reliable performance of digital electronic circuitry. In many applications, the occurrence of PD cannot be tolerated regardless of its damaging effect on electrical insulation. Manufacturers of high-voltage components and equipment, like high-voltage bushings and circuit breakers, have long been required to specify maximum PD levels at operating voltages.

Even under controlled conditions for well defined discharge-gap configurations, PD phenomena are complex, non-stationary stochastic processes that remain poorly understood. Extensive academic and industrial research, especially in Europe and Japan, is now underway to address the problems of understanding the physics and chemistry of PD and of developing improved PD-measurement methods and standards. At the present time, the existing national and international standards for PD measurement are being reviewed and revised [109, 110, 111]. It should be noted that the present standards for PD measurement tend to significantly influence the design of commercial PD-test equipment that are now sold by the manufacturers. Because the standards are conservative and represent a kind of lowest common denominator, they do not embrace many of the advances from recent laboratory research. In this respect they may tend to inhibit progress in practical implementation of new approaches to PD measurement and data analysis.

A major obstacle to the development of more useful and precise standards that reflect advances in the understanding and measurement of PD can be attributed to the conventional approach of quantifying PD magnitude in terms of charge (or apparent charge) usually expressed in picocoulombs (pC). Most commercially available PD measurement systems have an output meter or recording device that indicates PD level in pC. The problem is that the significance of a reading expressed in units of charge depends entirely on the reliability of the calibration procedure that is adopted. In general, for most high-voltage equipment, the calibration cannot be performed with a degree of precision sufficient to allow a meaningful assignment of charge units to a detected PD pulse [112]. This imprecision stems from a lack of knowledge about the equivalent circuit between the PD source, the location of which is seldom known, and the PD detector. For some electrical equipment, such as generators, the complexity of the intervening circuits may render calibration by conventional methods nearly useless [113]. Those intervening circuits may encompass a multitude of resonances. Moreover, in practical situations, like those encountered in substations, external noise can severely limit the sensitivity of PD measurements. Despite these problems and limitations, the importance and usefulness of PD testing remains. The possibility of abandoning PD testing has never seriously been considered. Therefore, the possibility of improving PD testing needs to be considered.

Relatively recent research on the properties of PD phenomena have shown that there may be alternative approaches to quantifying PD. These alternative approaches may be able to overcome the difficulties encountered when attempting to calibrate PD in terms of charge units. The alternative approaches may also provide more information about the nature of the defect site at which the observed partial discharges occur [114]. Information about such characteristics of the discharge as PD-pulse shape, pulse-to-pulse or phase-to-phase correlations of PD, and various conditional and unconditional PD-pulse amplitude and phase distributions can be used to provide a *fingerprint* of the phenomenon. Measurements of these discharge properties are not susceptible to the large uncertainties encountered in present attempts to calibrate PD detectors in charge units.

Advances have also been made in the application of acoustic and time-domain reflectometry techniques to pinpoint the location of PD in practical systems [115, 116, 117, 118], especially transformers and cables. Digital filtering techniques are presently being tested for automation of noise reduction which show promise for enhancing the sensitivity and reliability of PD measurements in the field [118, 119]. With the advent of fast PC-type computers that have expandable memory capability, it has now become feasible and relatively inexpensive to digitize and record large quantities of data about the properties of PD in a relatively short time [120]. Compact digital recording systems can now be employed both for factory and field testing of high-voltage apparatus. Under some conditions, on-line, real-time data recording may be advantageous and cost-effective.

Detailed analysis of recorded PD data can be performed at any time using sophisticated statistical methods. Permanent records of PD activity in equipment can be established from the time of commissioning. Presently, stochastic and neural network analysis techniques are being applied to the interpretation of PD data from laboratory experiments [120, 121, 122, 123]. These advanced analysis techniques show promise in allowing more meaningful use of PD data to provide a measure of insulation integrity. Although a *database* approach to PD measurement has obvious advantages, its adoption by the industry and its use in standard measurement practices still appears remote. More work is needed to validate this approach and to prove its cost-effectiveness before there will be wide-spread acceptance by the industry.

**Power-transformer lifetime extension:** Reliably extending service lifetimes of power equipment beyond the original design lifetimes is generally desirable. But such extension for power transformers is especially important because their replacement cost is so high. The average life of power transformers in service in the U.S. electric-power grid is 31.8 years for a design lifetime conservatively estimated at 30 years [74]. The failure rate ranges between 1.8 percent to 2 percent per year [124]. This indicates that power transformers are already being kept in service beyond their design lifetimes. Transformers represent the largest part of the capital investment in new transmission and distribution facilities, typically 20 percent of the total cost; no other single piece of equipment has greater effect on systems stability, or on the number of customers interrupted. The loss of a single power transformer can mean multi-million dollar losses for a utility or business. It is estimated that the utilities' investment in transformers in the United States is as high as several billion dollars.

EPRI has written a set of Guidelines for life extension of power equipment that includes discussions on major substation equipment maintenance practices, condition-assessment techniques, and decision-making process for equipment replacement or refurbishment [125]. Areas covered include routine maintenance and inspection procedures, common tests performed as part of condition assessment program, reasons for tests and use of test results, and factors to consider when deciding on refurbishment or replacement of substation equipment. This is closely tied to the RCM program described in the previous subsection.

The transformer full-load and overload capabilities are determined primarily by the hottest temperature in the windings. This temperature is not measured, however, but estimated from temperature measurements in the transformer oil either at top of bottom of the transformer, according to guides of the Institute of Electrical and Electronics Engineers (IEEE) [126, 127].

The biggest effect of heating in the transformer is deterioration of the insulation. Diagnostic tests include tensile strength and degree of polymerization of the paper insulation, and dielectric constant and loss measurements to monitor capacitance and conductance to determine the thermal age of the transformer. These measurements are very coarse and are not performed in real time. Improved condition monitoring through the use of in situ sensors together with better knowledge of the mechanisms of transformer aging are needed to provide a more realistic assessment of transformer health. This would permit the utilities to extend the usable lifetimes of power equipment beyond the conservative estimates used today without increasing the risk of failure.

## 2. TRADE

In the area of trade, there are at least two subjects of importance to the U.S. electric-power industry, its customers, and its equipment suppliers. The first is equity in trade, as affected by the accuracy of the metering of electricity. Trade in the domestic market dominates here. The approximately $200 billion of electric energy sold within the United States each year is subject to revenue metering at least three times between generation and end use, so metering affects at least $600 billion in transactions. Equity in trade is also important to international trade in electricity because the United States both imports electricity from, and exports electricity to its neighbors, Canada and Mexico [128]. A second trade subject of importance is access to foreign markets for electrical equipment manufactured in the United States. Access is sensitively dependent on the state of international test standards for electrical equipment. These subjects of metering accuracy and test standards are discussed further below.

### 2.1 Metering Accuracy

The distribution of the electric energy (kilowatt-hours) sold to various sectors of the U.S. economy, as a percentage of all electric energy sold, has shifted somewhat during the period from 1975 to 1995, as shown in Table 4 [129]. Sales to residential and commercial customers have grown in relation to sales to industrial customers.

**Table 4: ELECTRIC ENERGY SOLD, BY CONSUMING SECTOR (1975 and 1995)**

| | Percent | |
|---|---|---|
| Sector | 1975 | 1995 |
| Residential | 33.8 | 34.7 |
| Industrial | 38.2 | 33.5 |
| Commercial | 24.1 | 28.7 |
| Other | 3.9 | 3.1 |
| | 100.0 | 100.0 |

Note that residential customers require the largest number of points of delivery, followed by commercial customers, and then industrial customers. Thus, the relative growth in the residential and commercial sectors suggests that the suppliers of electricity must concern themselves with such key issues as equity in metering, and efficiency and load management, at a much larger number of delivery points.

For many years, meter manufacturers have produced polyphase induction watt-hour meters for commercial revenue metering. These meters track energy levels by counting the mechanical rotations of a magnetically driven disk that operates something like a motor. These meters have been developed to a high level of reliability and offer uncertainties of 0.5 percent in energy measurements. Now the meter manufacturers are producing new electronic watt-hour meters with improved capabilities. These meters have uncertainties approaching 0.05 percent. Further, depending on design, these meters can respond to frequencies much higher than the 60 Hz fundamental of the power line; therefore, they can measure the energy in harmonic frequencies (multiples of 60 Hz) as well.

Presently, the performance of both induction and electronic watt-hour meters used in revenue metering is established by a chain of calibrations. The highest level in this chain is the national standards maintained by NIST. NIST uses the national standards to calibrate a relatively small number of highly accurate intermediate standards from industry, about 50 per year. These intermediate standards are themselves electronic watt-hour meters. These standards are then used to calibrate an even greater number of other intermediate standards, and so on, in a fan-out pattern until there are enough intermediate standards to support the calibration of an estimated 10 million watt-hour meters in the United States each year. At each point of calibration in this chain, the uncertainty achievable is inevitably degraded (increased). Therefore, NIST must maintain a very low level of uncertainty to assure that the uncertainty remaining at the end of the chain is sufficiently low.

At present NIST can calibrate the highest level of intermediate standards to an uncertainty of 0.01 percent in the absence of significant harmonic content. This level of uncertainty enables the calibration chain to support revenue meters with uncertainties down to 0.1 percent. This capability has been sufficient to date because meter manufacturers have not yet been marketing their new electronic watt-hour revenue meters as having uncertainties under 0.2 percent. However, if the meter manufacturers wish to market their revenue meters at uncertainty levels under 0.1 percent, then NIST's capability will have to be improved to provide adequate support through the calibration chain. Further, if the meter manufacturers or their customers want the sensitivity of the meters to higher frequencies evaluated by the calibration process, then NIST's capability will again have to be improved. The issue of harmonics is discussed further in Section 4.2 of this chapter. The electronic meters also have the ability to monitor the quality of power delivered to the load, which inherently requires the ability to respond to higher frequencies. The questions of which parameters are the most important to monitor are being addressed by standards committees and are discussed in Section 4 of this chapter.

## 2.2 International Test Standards

The committees of the International Electrotechnical Commission (IEC) that set international standards for electric-power equipment comprise world membership but are predominantly European. Further, the participants often represent multinational European companies that can send representatives from more than one country to a given standards-writing committee. In contrast, the standards that U.S. manufacturers of electric-power equipment follow are sourced largely in the committees of the Institute of Electrical and Electronics Engineers (IEEE); these committees have a largely North-American membership. In this divergence, there is potential at least for development of international standards by the IEC that promote the interests of European companies at the expense of U.S. manufacturers. Standards may then be *de facto* trade barriers, especially if the U.S. companies do not have access to the same measurement capability as their European competitors for proving compliance. Under these conditions, U.S. companies can be effectively excluded from selling in

Europe and other parts of the world. The goal of ensuring fair trade in electrical-power equipment gives rise to the need for maintaining equivalence in international test standards and supporting measurement capability so that all manufacturers can meet the same requirements.

An important example of this problem arises in recent revisions of IEEE [98] and IEC [99] test standards governing high-voltage test techniques used for ensuring reliability of electric-power equipment. Although the standards do not define tests for specific equipment, such as transformers and generators, they do establish requirements for the standard waveforms and measurement systems used in the equipment testing. The two standards have traditionally been nearly identical in their requirements, but in the latest revisions there have been some important changes resulting in differences between them. Both have formalized the concept of reference systems; reference systems have stricter measurement requirements placed upon them and are used to calibrate other measurement systems intended for routine test-laboratory use. However, the IEC standard introduces the concept of accredited laboratories and measurement systems, whereas the IEEE standard does not. Such a difference may result in a trade barrier.

# 3. GLOBAL WARMING AND HEALTH EFFECTS

## 3.1 Airborne Emissions

Airborne emissions have been of particular concern to the electric utilities since the implementation of the Clean Air Act of 1990. Specifically, the utilities' concerns center around two aspects of the act: (1) global warming (related primarily to emissions of $CO_2$); and (2) acid rain (related primarily to the emission of $SO_2$). The matter of global warming is currently the lesser concern of the two since electric-power plants account for less than one third of all $CO_2$ emissions in the United States. Additionally, it can be argued that the conversion of fossil-fuel devices to electrical replacements (as discussed below) actually reduces the emission of global warming gases.

However, the production of $SO_2$ is of more immediate concern to the utilities since 57 percent of all electricity produced in the United States is generated in coal burning plants (which emit $SO_2$); and the industry is being required to reduce $SO_2$ emission by 10 million tons by the year 2000 [65]. This change is being enforced by issuing *allowances* for $SO_2$ production [130]. At the present time there are sufficient allowances and adequate technologies in existence for the utilities to operate. However, there is concern that, if new plants are built, there will be insufficient allowances available to permit operation of these plants. The answer to this concern is being sought from new technologies such as gasified coal burners and improved flue-gas scrubbing.

### 3.1.1 Sulfur hexafluoride

Sulfur hexafluoride ($SF_6$) is the most commonly used insulating gas in electrical systems. Such use accounts for about 80 percent of all uses of $SF_6$ produced worldwide [131]. The extremely high global warming potential and long atmospheric lifetime of $SF_6$ [132] has recently raised the concern of the EPA and others [133] about the environmental impact of the inevitable release of $SF_6$ into the atmosphere from transformers, switchgear, gas-insulated substations, and transmission lines.

Recent measurements [134, 135] indicate that the concentration of $SF_6$ in the earth's atmosphere is increasing at a rate of 8.7 percent per year. Because $SF_6$ is an efficient absorber of reflected solar infrared radiation and because its lifetime in the atmosphere is estimated to be between

800 and 3200 years [136], its global warming potential is more than 20,000 times that of $CO_2$. At present, a leak rate of 1 percent per year of $SF_6$ from power system equipment is considered acceptable, which means that in a hundred years nearly all of the $SF_6$ now confined by the electric-power industry will end up in the atmosphere. Moreover, there are no economically feasible methods in place to dispose of used $SF_6$, if that $SF_6$ is considered too contaminated for further use as an insulating or arc interrupting gas in electrical equipment.

The present industrial practices for handling $SF_6$ are no longer considered adequate or acceptable. Proposals for new methods of controlling the release of $SF_6$ into the atmosphere are under consideration by appropriate national and international standards committees, such as the IEEE Committee S-32-11 on Gaseous Dielectrics. Among the proposals under consideration are: (1) development of more realistic standards for the purity of recycled $SF_6$ used in equipment; (2) elimination of unnecessary scheduled maintenance of $SF_6$ circuit breakers which involves release of some $SF_6$; and (3) replacement of $SF_6$ with higher pressure replacement gases, such as $N_2$ or $SF_6/N_2$ mixtures that have comparable dielectric strength. The use of $SF_6/N_2$ as an insulating gas in some types of high-voltage bushings, transformers, and bus lines is a promising intermediate step in controlling the release of $SF_6$ [137]. Of immediate concern for development of new $SF_6$ purity standards is $CF_4$ contamination. It is known that $CF_4$ builds up in $SF_6$ used in circuit breakers, reduces the dielectric strength of $SF_6$, and cannot be readily removed by the usual gas absorbers and filtration methods. More work on the effect of $CF_4$ on the performance of $SF_6$ as an insulating gas is needed. The acceptance by the industry of replacement gases such as $SF_6/N_2$ mixtures will also require considerable additional testing and research in order to determine fully the technical and economic impacts of such conversions.

Manufacturers of $SF_6$ are shifting their production capacity to other products; and the cheap, abundant supply of $SF_6$ that the utilities have enjoyed is not likely to continue in the future. In response to concerns raised about the environmental issues surrounding the use of $SF_6$, the IEC has undertaken the task of preparing a guide for recycling $SF_6$. The guide seeks to establish acceptable levels of impurities for used and/or reprocessed $SF_6$ and to recommend practical methods that may ensure that these levels are maintained. Three criteria have been recommended: total content of decomposition by-products, humidity, and $CF_4$ content.

In a recent meeting of the IEEE Committee on Gaseous Dielectrics, the likelihood that the manufacturers of $SF_6$ would not be interested in reprocessing used $SF_6$ was addressed. Thus, it seemed that the recycling of $SF_6$ would more likely be done by the end user with, perhaps, a few third-party vendors providing services for the safe disposal of spent gas and/or the recovery of severely contaminated gas. Since, in this scenario, $SF_6$ would be recovered and reprocessed in small lots by the end user, the methods used for chemical analysis would need to be inexpensive and readily applied in the field. The existing IEC and ASTM standards for establishing $SF_6$ purity are based on condensed-phase (liquid) analysis and are not likely to apply in this case, since gas recovered in small lots would probably not be liquefied. Thus, there is an immediate need among the end users of $SF_6$ for the development of gas-phase analytical methods. Also needed is further guidance in recommending acceptable levels of contaminants. Finally, there is a need for the development and dissemination of methods for abatement of $SF_6$, that is, for recommended filtering materials and procedures that may be used to limit exposure of personnel to used $SF_6$.

### 3.1.2 Electrical replacements for fossil fuel devices

**Electric vehicles:** Electric vehicles have long been envisioned as a possible replacement to automobiles in order to reduce airborne emissions. In many respects the technologies exist to produce functional electric vehicles, although a multitude of desirable technological improvements have been identified [138]. One of the biggest technological stumbling blocks continues to be the development of quick-charging, long-lasting, reliable, safe, and lightweight batteries. Related areas of strong interest and concern for the electric-power utilities are: (1) how will the advent of electric vehicles affect the existing power load; (2) how will the presence of thousands of high-power battery chargers affect the power quality of the system; (3) what safety issues should be addressed; and (4) what standards for electrical connections will be implemented.

The recent flurry of activity on electric vehicles was primarily driven by non-market forces, specifically by the California legislation [139], described below, and then by the NEPA legislation [92] which mandates that a fraction of fleet vehicles be powered by alternative fuels, with electricity as one of the possible alternative fuels.

The California legislation was written to address the issue of air quality; that legislation contained no additional regulation of power-plant emissions and was written entirely to address the problem of vehicle emissions. The onus for complying with the legislation was on the automobile manufacturers in that they were required to produce and sell vehicles at the levels that were mandated by the California legislation. The utilities did assume some responsibility in supporting the goals of the legislation by actively working with vehicle manufacturers and other interested parties to facilitate the entry of electric vehicles into the market. However, their direct responsibility in supporting the legislation was in delivering reliable high-quality power to the battery charger, which was perceived to be readily achievable.

The primary concern expressed by the utilities was that no institutional barriers should impede the entrance of electric vehicles to the market, and the utilities have taken an active role in promoting the use of electric vehicles. The EPRI-sponsored Electric Vehicle Infrastructure Working Council (IWC), for example, was formed to address issues of adequate infrastructure. Participants include: utilities, vehicle manufacturers, government agencies, and testing labs.

The utilities' calculations show that, at the levels mandated by the California legislation, the present generation and transmission capacity can support electric vehicles well into the next century, provided that the added load due to vehicle charging can be properly managed [140]. That is, most vehicle charging would be structured to occur during off-peak hours. There is some concern that the local distribution system may need to be upgraded to accommodate the added load. For this, the utilities need accurate information to model the load added to the local distribution systems due to vehicle charging. These data include: estimates of market penetration, demographics for vehicle ownership, patterns of vehicle use, and load profiles for battery chargers.

There is the possibility of degradation of power quality due to battery chargers, which is of concern to the utilities. The vehicle charger load corresponds approximately to the electrical load of an average household, and this load would be switched in and out according the battery charging cycle. The utilities need, and are actively developing, procedures to ensure the power-quality performance of battery chargers.

There is added exposure of the vehicle occupants to magnetic and electric fields and at least some public perception of added risk to health. The IWC did view magnetic fields measurements as a significant issue, and EPRI was supporting the development of measurement procedures for electric vehicles. However, as a matter of policy, the IWC had chosen not to define magnetic field exposure as a health issue.

In summary, there are significant technical challenges that need to be overcome to make electric vehicles viable alternatives to internal combustion engine powered vehicles; however, these challenges do not lie with the utilities.

**Lawn mowers:** Interestingly, internal combustion lawn mowers have recently been identified as a substantial source of air pollution [141]. In fact, new lawn mowers purchased in 1997 will have to meet EPA-dictated limits on emissions of hydrocarbons, carbon monoxide, and nitrogen oxides. The use of electric lawn mowers is being promoted by both the utilities and environmental groups as an inexpensive and clean alternative to gasoline powered mowers. (A year's worth of lawn mowing with an electric mower costs less than $4.) No significant technology needs are evident in this area, but this does represent a good example of the trend toward using electricity to reduce airborne emissions.

## 3.2 Electric and Magnetic Field Effects

Since the early 1970s there has been a concern over the possible effects on human health of electric and magnetic fields (EMFs) associated with electric-power equipment and appliances. The concern was heightened in 1979 because of an epidemiological study performed by Wertheimer and Leeper that indicated childhood deaths from cancer were two to three times more likely if children lived within 40 m of a high-current power line. Exposure to magnetic fields was identified as a possible factor in their findings, but the field strengths used in the study were estimated, not measured [142]. Many subsequent studies have been made, but the evidence to date is inconclusive with no incontrovertible evidence relating fields to cancer. A working group of the Conférence Internationale Des Grands Réseaux Electriques (CIGRE) concluded that the evidence pointing to magnetic fields as a cause of cancer is weak, and the risk factor is likely to be low. But future epidemiological studies on human populations may be inadequate to definitively answer the question of risk; exposure studies on animals and cells may play a critical role [143].

The accurate measurements of EMFs is of great importance in both epidemiological and laboratory-exposure studies. For example, three-axis magnetic field probes used for determining the field strengths in air, such as in the vicinity of power lines and electrical appliances, measure the average field within their volume. For non-uniform magnetic fields, the average that is measured depends upon the orientation of the probe with respect to the magnetic field source and the size of the probe. One technical challenge that has been addressed is the determination of the probability distribution of errors because of averaging effects of a three-axis probe when measurements are made near many electrical appliances [144]. The study illustrates the care that must be taken when these probes are used for field measurements near appliances, where the error may be close to 20 percent of the actual value.

Three major technical challenges related to studies of the biological effects of extremely-low-frequency induced electric field exposures for cells and tissue are these: (1) modeling and experimental verification of induced electric field exposures for cells near confluence, i.e., closely spaced cells during in vitro studies; (2) experimental verification of equivalent electric-circuit models assumed for cell membranes having ion conducting channels; and (3) noninvasive measurements of currents induced in biological systems by external magnetic fields. These are discussed below.

### 3.2.1 Modeling and experimental verification

Induced electric fields in cell culture media for widely dispersed cells in suspension are readily modeled, as illustrated in a number of publications [145, 146, 147, 148, 149]. The fields are also readily verified experimentally [145, 148, 149]. The success of the modeling hinges on the fact that widely dispersed and suspended cells have negligible proximity effects on each other. In a common configuration for cell-culture studies, cells are grown on the bottom of cell-culture dishes close to one another. The electric field at the surface of a given cell membrane, which is thought to be the *site of action* for the electric field, will be influenced because of perturbations of the field by nearby electrically polarized cells. These cells can be thought of as dielectric objects, with interiors of electrically conducting cytoplasm. The dielectric objects also have surface charges, arising from the ions in the culture medium. The problem is further complicated by the various shapes that different cell species can have while attached to the bottom of the culture dish. The problem is twofold, that is, theory must be developed and must also be verified experimentally with measurements. For example, while there is theory to describe a single, charged spherical dielectric in a uniform electric field, the theory does not consider field perturbations at the surface of the sphere due to proximity effects of the nearby charged spheres [150]. While measurements of electric fields in culture medium can be made with a dipole electric-field probe, measurements of the perturbed electric field near the surface of cell membranes will be more difficult; that is, the perturbing effects of the field probe must be understood. It is noted that fluorescence techniques that have been used to measure membrane potentials will not work in the present case because of the very low electric-field strength levels (~10 μV/cm).

### 3.2.2 Experimental verification of equivalent-circuit models

An electrical model of a biological cell used by researchers includes the assumption that the cell membrane and ion conducting channels that penetrate the membrane can be represented as a capacitor (the membrane) and resistors (the ion channels) in parallel [151]. One method for verifying aspects of this model is by applying alternating extremely-low-frequency electric fields across a planar membrane and examining the real and imaginary components of the current through the membrane for one or more ion channels, that is, as the frequency of the electric field is varied, the rms value of the current through the resistors should remain unchanged. The current levels are in the picoampere range and a careful accounting of the phase shifts that occur in the detection circuitry is required to monitor the resistive current successfully.

### 3.2.3 Non-invasive measurements of currents induced in biological systems

Invasive measurements in rat cadavers using a dipole electric-field probe have been described by D.L. Miller [152]. While there are numerical modeling techniques for calculating currents and electric fields induced in biological systems by external extremely-low-frequency magnetic fields [153], experimental verification of the theory using noninvasive measurement techniques has not been reported in the technical literature. That is, while measurements can confirm gross predictions of the model, such as total current passing through the feet of an exposed human or animal on a grounded surface, no experimental checks can be made regarding the current in different regions of a heterogeneous body [154, 155].

## 4. POWER QUALITY

In the last decade, power quality has emerged as a major topic of interest to electric utilities and their customers, and indirectly to almost all of the manufacturers of equipment that depend on a supply of *good quality* electric power. This emergence has two principal causes: increased sensitivity of some electronic loads with greater dependence upon their undisturbed operation, and the development of sophisticated instruments capable of on-site monitoring of disturbances in the power supply. The major types of disturbances are surges, swells, sags, interruptions, and harmonics. Surges are transient overvoltages of several times the normal line voltage and lasting only microseconds. The largest threat from this type of power disturbance is the breakdown of electrical insulation or semiconductors, either in the power equipment in the power system or in the end users' equipment. Swells are overvoltages up to twice the normal line voltage which last for up to several cycles of the power-frequency voltage. Voltage sags are under-voltages as low as nearly zero, for times ranging from milliseconds to seconds. What utilities call an *interruption* varies with interpretations of regulations issued by public service commissions. Generally, an interruption of a few cycles is not reported, and yet it can cause complete shutdown of an industrial process or data-processing system. Harmonics generated by non-linear loads are also of growing importance with the proliferation of electronic equipment using a capacitor-input rectifier in their internal power supplies. Significant imbalances due to harmonics can overload neutral conductors and wye-delta distribution transformers.

Equipment manufacturers view making equipment more immune to disturbances as an expense which would place them at a disadvantage to their competitors. Of course, purchasing low-priced (but disturbance-sensitive) equipment can appear cost-effective in the short run but be more costly in the long haul. Thus, the development of test methods and performance criteria for equipment immunity is needed by manufacturers of sensitive equipment, by the electric utilities, and by end users.

In the past, detecting power system disturbances was not an easy task for field instruments, except for the more obvious disturbances associated with significant voltage sags causing lights to dim or causing full interruptions. Major organizations, such as the U.S. Navy, IBM, General Electric, and Bell Laboratories, developed special, and sometimes bulky, recording systems. In the mid-1980s, a revolution occurred in the instrumentation: Voltage disturbance recorders were developed, with on-board processing and hard-copy print-out capability; and these recorders were no larger than a large briefcase. These were easy to connect wherever disturbances were suspected, and hundreds of them were deployed. This proliferation of disturbance monitors raised awareness of power quality as a utility concern.

The proliferation of disturbance monitors also demonstrated the incompatibility of data recorded by instruments made by different manufacturers. The manufacturers used different algorithms to process the measurement data and to provide the most meaningful interpretations of the data. Additionally, the definitions used by different manufacturers to describe a disturbance were not the same. For instance, when reporting a *surge*, one manufacturer filtered out the power-frequency voltage, calling the *surge* only the deviation from the sine wave, while another manufacturer would report as the *surge* the actual peak that occurred, including the sinewave voltage.

A recent summary of surveys of the electrical environment pointed out the difficulty of characterizing that environment in the absence of standard practices more generally. That is, the results of the survey were complicated not only by differences in instrumentation, as discussed above, but also by several other factors. These factors included variations in the threshold settings used in each survey, variations in the monitored locations, and variations in the sources and propagation characteristics of the various power disturbances [156]. Melhorn and McGranahan [157] conclude the following: "With advances in processing capability, new instruments have become available that can characterize the full range of power quality variations. The new challenge involves characterizing all the data in a convenient form so that it can be used to help identify and solve problems." Ten years after this problem was recognized, and after an IEEE working group was created to develop a Recommended Practice addressing this problem, a standard was published by IEEE (Std 1159). This standard attempts to address the situation but has little chance, by itself, to make manufacturers change their entrenched algorithms. In the course of updating of IEEE standards, it is possible that the problem might be addressed. Upon the request of instrument users, task forces to that working group have been established to develop standards and protocols on sampling rates, data processing, and reporting format.

## 4.1 Correction of Power Distortions

Several types of the FACTS devices that utilize power-electronic controllers to regulate the flow of electric power through transmission lines can also correct for power-quality problems. The FACTS devices were described in Section 1.1.1 of this chapter. When used in distribution systems for improvement of power quality, such devices are referred to as *custom power devices* [158]. They are described in the next section.

### 4.1.1 Custom power devices

Minor voltage disturbances on distribution circuits can have major consequences. Even a voltage sag for as little as 0.1 second can cause heavy-production and product-quality losses. Substandard power is expected now to be limited to as little as one half-cycle without having significant effects. When an outage or voltage sag exceeds a few cycles, motors, machine tools, and robotics cannot maintain the precise control of the processes they perform. Lightning strikes are indirectly responsible for a large percentage of all power-system outages and dips, with a typical strike causing flashover and circuit breaker opening for 5 to 30 cycles over a large service area. Other sources of disturbances include motor starting, capacitor switching, faults, and intermittent heavy loads.

Recovery from a disturbance can lead to further disturbances. Consider the action of a *recloser*. A recloser is an automatic, normally closed circuit breaker that opens when a fault occurs and attempts to reclose, up to several times for some models, before locking out. If the fault is not cleared, usually by the third attempt, the recloser locks out, interrupting power to customers. Neighboring feeder circuits witness marked voltage dips during the reclosing intervals; the line voltage is depressed or distorted for several cycles after reclosing due to the high in-rush current of the motor loads and various circuit oscillations that occur during each startup.

Customers may employ their own *local solutions* to power irregularities, such as uninterruptible power supplies (UPS), surge suppressors, backup generators, and alternate feeders with mechanical switches. Some of these solutions are costly, of the order of hundreds of dollars per kilowatt-hour, and inefficient, having as high as 20 percent energy loss [158].

Custom power devices, applied to the distribution system itself, can provide more *global solutions* to power quality problems. They are the dynamic voltage restorer (DVR), the solid-state breaker (SSB), and the distribution-system version of the static compensator (STATCOM). The transmission-system version of the STATCOM was discussed in Section 1.1.1 of this chapter. The DVR is similar to that of the STATCOM except that the DVR transformer is connected in series with the line, while the STATCOM transformer is connected across the line, as a shunt. The SSB can be used to obtain faster opening and reclosure times than conventional circuit breakers. The SSB consists of back-to-back thyristors in series to get the desired voltage rating. There are two types of SSBs: the silicon-controlled rectifier (SCR) type and the gate-turnoff thyristor (GTO). The SCR breaker turns off at the first zero of the current which, although it has a delay of possibly a few milliseconds, may still be acceptable for many applications. The GTO turns off immediately when a control pulse is received at the gate input, providing instantaneous control of the distribution circuit. The SSBs can be used to switch from the primary feeder circuit to the secondary very quickly when a fault or other disturbance is detected on the primary feeder.

The technical needs for the successful implementation of custom power devices are similar to those described for FACTS technologies in Section 1.1.1 of this chapter: the need for numerous, low-cost, accurate sensors to be installed throughout the transmission systems to monitor power-system disturbances, and the need for communication systems to be put in place to monitor the sensors and to coordinate the operation of the custom power devices. Custom power devices will rely on rapid and accurate fault location to respond correctly to disturbances and to maintain high power quality.

#### 4.1.2 Surge suppressors

The widely used term *surge suppressor* is symptomatic of some misconceptions that still pervade the industry. Properly speaking, a surge can be diverted, but never suppressed. Devices offered by the industry under the IEEE-approved name of surge-protective device (SPD) range from the large arresters used throughout a utility system to tiny electronic-level components at the line-cord entry of appliances. Since the introduction of low-cost SPDs using metal-oxide varistors in the mid-seventies, their use has mushroomed to the point where almost every measurement of surge voltages inside buildings has become irrelevant because such measurement now yields only the residual voltage from the SPD action. New instrumentation is needed to characterize the surge environment, capable of measuring the energy that may be involved in a surge event, not the voltage appearing across the line.

Another issue resulting from the proliferation of consumer-type SPDs, and the highly competitive nature of the business, is that some improperly designed SPD packages may present a fire hazard because of uncontrolled failure modes. The Underwriters Laboratories have recently recognized that potential problem and are now in the process of promulgating a revised standard which addresses this concern.

Traditionally, the electric utilities have viewed their domain as bounded by the revenue meter at the customer's premises, for power quality as well as other concerns. Within their normal domain, some electric utilities are now offering SPDs for installation at the service entrance to support power quality. Increasingly, however, the utilities are working on the other side of the revenue meter, too. For example, they are offering plug-in SPDs to be installed by end users. The motivation is two-fold: offer the customer a service that will minimize customer complaints, and create an opportunity for additional revenue for the utility. Further, the electric utilities are increasingly open to discussing with customers instances of power-quality problems that are related to the fixed wiring or equipment of the end user, rather than to the utility system proper.

#### 4.1.3 Lightning protection

Lightning strikes to power-transmission and power-distribution equipment are a major cause of system failures and power interruption in the United States. The utilities have an obvious interest in reducing the vulnerability of power systems to the direct and indirect effects of lightning. Research sponsored by EPRI, Hydro Quebec, and others continues to address the problems of achieving a better understanding of lightning and of designing better lightning protection systems [159].

New techniques for lightning protection are presently being tested [160]. These include early streamer emission [161] and laser triggering [162]. Although standards for conventional lightning protection systems have been issued by the National Fire Protection Association and others, these do not encompass new techniques and are not always applicable to power-system components such as overhead transmission lines. Generally, proposed new lightning protection systems are significantly more costly than conventional systems, and unresolved issues remain about the cost-effectiveness of these new systems. At issue, for example, are the tests that have been performed to measure the comparative effectiveness of different lightning-protection systems [159, 163]; and questions have been raised about the validity and usefulness of laboratory simulations of lightning [164]. More work is needed to develop and validate model calculations of lightning-protection effectiveness as well as both laboratory and outdoor tests of protection systems.

## 4.2 Harmonics

The proliferation of adjustable-speed drives (ASDs) and the presence of other non-linear electrical loads in distribution systems can cause significant degradation of power quality. They generate harmonics and subharmonics of the 60 Hz power frequency. These unwanted frequencies distort the power waveforms and can interfere with the operation of sensitive electronic equipment, both in other parts of the plant generating the harmonics and in the distribution system. Non-linear loads draw a non-sinusoidal current and return the distorted current waveform to the distribution system. The distorted current waveform flowing through the distribution system impedance causes distortion of the voltage waveform.

In addition to the corruption of power quality, the presence of non-linear loads can result in significant currents in the neutral conductors. Distribution systems are designed so that the three-phase, four-conductor circuits supply closely balanced single-phase loads and so that the neutral conductor carries a minimal current imbalance. According to earlier versions of the National Electric Code (NEC) [165], the neutral conductor may be downsized from the phase conductors for cost savings. Non-linear loads cause addition, not cancellation, of phase currents in the neutral which can lead to overheating of the neutral-current return conductors and of wye-delta transformation transformers, resulting in shortened transformer lifetimes. More recent editions of the NEC have recognized this problem and have stipulated appropriate sizing of the neutral conductor.

The distorted voltages and currents produced by non-linear loads, such as ASDs, can also affect the accuracy of the metering of electric power and energy. Typically, it is the current waveform that is corrupted by the non-linear loads. If the voltage waveform remains sufficiently pure, that is, if it does not contain significant harmonic components, then the meter registration remains within the design specifications in general. However, if the voltage waveform is distorted significantly, then the metering errors can become large. Filipski and Arseneau have measured various types of wattmeters and watt-hour meters and have demonstrated that errors exceeding 1 percent in induction watt-hour meters can occur with waveforms typical of those measured for ASD loads [166]. They recommend avoiding the use of inductive meters in nonsinusoidal situations, both for this reason and because of possibility of mechanical damage, which can occur when the meter is subjected to a change in the direction of energy flow several times per minute.

The two somewhat different technical challenges here: (1) to mitigate harmonic content in the first instance, and (2) to ensure metering accuracy in the presence of significant harmonics when they do arise. Harmonic content may be mitigated through the use of the custom power technologies, such as the STATCOM described above, which can absorb harmonics generated by the load, and also through the use of filters inserted in the distribution system. EPRI has a project to design hybrid transmission-system filters and to demonstrate them in the field. These hybrid filters comprise a combination of passive and active filters to minimize transmission-system harmonics. The hybrid filters are intended to overcome the problems associated with the use of the existing technology of passive filters, such as resonance problems that occur with changes in power-system impedance and/or component values. The hybrid filters are expected to be lower in overall installed cost than current passive-filter technology for large installations [125].

### 4.3 Power Outages

The most severe form of loss of power quality is the total power outage. This may result from storms, excess loads, broken power lines due to accidents, and sometimes unknown causes [167]. During times of outages, the most immediate concerns are the identification of the extent of outage and the determination of the cause. Currently, this information is derived from customers' complaints and subsequent on-site verification by utility personnel. In the future, these needs could be resolved by remote meter reading and/or sensors on all distribution transformers that would allow the utility to immediately determine the location of faults, without relying upon customers' phone calls [125].

Another area being addressed is the need for damage-assessment data for power systems after a severe storm. During and after severe storms, the conventional communications and instrumentation systems may be disabled. Real-time satellite event monitoring may be useful to provide high-resolution image data that can be used to assess the extent of damage and support the dispatch of repair crews. Night-imaging data may also be useful in identifying malfunctioning street lighting [168].

## 5. SUMMARY

This chapter outlined the most significant technical needs that arise in response to several drivers of the electric-power industry: (1) efficiency, reliability, and stability; (2) trade; (3) global warming and health effects; and (4) power quality. Those needs reflect challenges to the generation, transmission, distribution, and use of electricity. The needs arise from technologies that play quite different roles in the overall picture: some may cause problems on the power lines; some may increase sensitivities to those problems; or some may solve problems. Here are examples of each type. Switching power supplies offer high energy efficiency but can contribute to irregularities on the power lines. Low-power microelectronics have provided tremendous capabilities at minimal cost but can be highly sensitive to power-line irregularities. Technologies such as optical sensors, power-flow controllers, and superconducting power equipment may prove important to the solution of power problems.

The next chapter begins with a summary of the technical needs described in this chapter and then distills from that summary the most critical long-term and short-term needs for which NIST assistance seems needed, with a special focus on electrical measurements for transmission and distribution.

# CHAPTER THREE: IMPLICATIONS FOR NIST

In this chapter, the technical needs discussed in Chapter Two are extracted and related to the measurement capability or related technology needed from NIST. While the needs addressed arise in the generation, transmission, distribution, and use of electricity, the focus here is principally on transmission and distribution, and specifically on electrical quantities. Other needs may be just as important. Based upon the information in the first two chapters, the most critical long-term and short-term needs related principally to electrical quantities are identified.

Further, the focus here is on the technical needs driven by the major changes taking place in the electric-power industry and by that industry's effort to respond by employing appropriate technologies, including emerging technologies. This chapter does not address, in as much detail, technical needs of a long-standing nature, such as those related to reliable, high-quality calibration services. NIST is currently meeting these needs and will endeavor to do so for the foreseeable future.

NIST's role in support of the electric-power industry and its customers is much like its role in support of other U.S. industries and their customers. NIST does not develop measurement capability that individual companies can provide for themselves. Rather, NIST acts when needed measurement capability is beyond the reach of individual companies and when providing that capability will have high economic impact for the nation. Companies seek NIST's help for several reasons. The companies may need NIST's special measurement expertise, which extends across many fields of technology, for the development of new measurement capability or for the comparison or validation of existing measurement capability. The companies may need NIST's impartiality, which enables NIST's measurement solutions to be adopted by all companies in an industry with confidence. The companies may need NIST's imprimatur as the lead-agency of the U.S. Government for measurements, which enables NIST to support U.S. interests when measurement barriers bar U.S. products from foreign markets. Further information on NIST's role is provided, in detail, in Chapter 2 of *Measurements for Competitiveness in Electronics* [169].

## 1. SUMMARY OF TECHNICAL NEEDS

In Table 5 below, 42 technical needs of the electric-power industry are presented in the third column. The order of presentation is the order of discussion in Chapter Two, not a priority order. The specific sections of Chapter Two in which these needs were presented are referenced in the second column. The implications for NIST research are listed in the fourth column. The NIST organizational units (OUs) that could appropriately respond are listed in the fifth column. The status of NIST's response is indicated in the sixth column: *current* if a responsive research program is currently in place; or *none* if no research program is currently in existence. It should be noted that a designation of *current* implies only that some portion of the need is being addressed, not necessarily the entire need.

It should also be noted that individual needs listed in Table 5 may be related to other needs in the table. For example, some of the needs represent subsets of larger needs that are present elsewhere in the table. The manner in which each technical need is presented in Table 5 is indicative of the manner in which it was presented in the literature or in the interactions from which the information in Chapter Two was derived.

Of the 42 needs listed in Table 5, NIST is currently responding to 15 of them by applying available resources, as indicated by the annotations in the sixth column. This level of response indicates both that a very large number of needs are already being addressed, and, unfortunately, that a very large number are not, reflecting the difficulty of responding to the needs of such a huge industry.

Because of the emphasis here on electrical quantities, a very large fraction of the needs shown in Table 5 fall within the purview of the Electronics and Electrical Engineering Laboratory, and specifically, the Electricity Division at NIST, which has primary responsibility for electrical measurements at NIST.

**Table 5: TECHNICAL NEEDS AND IMPLICATIONS FOR NIST DERIVED FROM CHAPTER TWO**

**Key to Abbreviations for Organizational Units (OUs)**

| | | | |
|---|---|---|---|
| CSTL | Chemical Science and Technology Laboratory | MSEL | Materials Science and Engineering Laboratory |
| EEEL | Electronics and Electrical Engineering Laboratory | PL | Physics Laboratory |
| ITL | Information Technology Laboratory | TS | Technology Services |
| MEL | Manufacturing Engineering Laboratory | | |

| | Section | Technical Needs | Implications for NIST | OU | Status |
|---|---|---|---|---|---|
| 1. | 1.1.1<br>1.2.1<br>1.2.4<br>4.1.1<br>4.3 | Low-cost, accurate sensors for monitoring transmission systems for real-time control, state estimation, and monitoring system disturbances (i.e., power quality) | Test, characterize, calibrate, and develop sensor performance and reliability. | EEEL | current |
| 2. | 1.1.1<br>1.2.1<br>1.2.2<br>1.2.4<br>4.1.1<br>4.3 | Communication system to query and control transmission, distribution, and demand-side management systems sensors from a control center | Develop standard communication protocols and architecture. | EEEL, ITL | none |
| 3. | 1.1.2 | Insulation for cryogenic power devices, such as cables, motors, and transformers | Measure electrical insulation performance under cryogenic conditions. | EEEL | none |
| 4. | 1.1.2 | Verification of AC power transfer efficiencies in high-temperature superconducting (HTS) power devices | Develop measurement methods for determination of AC power transfer efficiencies in HTS devices. | EEEL | none |
| 5. | 1.1.2 | Determination of HTS device performance under fault conditions | Develop measurement methods for determination of HTS device performance under fault conditions. | EEEL | none |
| 6. | 1.3 | Increased efficiency and equipment lifetime in power generation | Improved fluid-flow measurements for power-generation facilities. | CSTL | current |
| 7. | 1.3 | Increased efficiency in power generation | Improved temperature measurements for controlling coal-fired boilers. | CSTL, MEL | none |

| | Section | Technical Needs | Implications for NIST | OU | Status |
|---|---|---|---|---|---|
| 8. | 1.4.1 | Improved materials for lighting | Evaluate performance of materials under wide range of lighting conditions. | PL, CSTL, MSEL | none |
| 9. | 1.4.1 | Fundamental data for the modeling, understanding, and design of new light sources | Measure, accumulate, evaluate, and disseminate standard reference data related to the chemistry and physics of light emission. | PL,TS, EEEL | current |
| 10. | 1.4.2 | Methods to accurately measure efficiencies of high-efficiency motors and transformers | Develop standard methods for efficiency testing of motors and generators with low uncertainties. | EEEL, MEL | current |
| 11. | 1.4.2 | Reduction of effects of harmonics produced by variable-speed drives (VSDs) | Develop mitigation techniques to reduce harmonics.<br>Develop measurement techniques to characterize harmonics produced by VSDs. | EEEL | none |
| 12. | 1.4.3 | Environmentally safe refrigerants for heat pumps | Test refrigerants with potential for reducing ozone-depletion and global warming. | CSTL | none |
| 13. | 1.2.1 | Low-cost metering-grade voltage and current sensors to measure bulk power exchanges that occur during wheeling agreements and during exchanges with independent power producers | Test, characterize, and calibrate performance and reliability of all newly introduced sensors. | EEEL | current |
| 14. | 1.2.1 | Ability to calibrate remote sensors while in service | Develop and validate methods for self-referencing, model-referencing, or remote-referencing of sensors. | EEEL | none |
| 15. | 1.2.1 | Timing coordination of remote sensors for real-time control and system monitoring | Develop and verify method for sensors to synchronize data with universal timing tag. | PL | none |
| 16. | 1.2.1 | Optical current and voltage sensors as inexpensive, reliable remote sensors | Validate stability, sensitivity, linearity, and accuracy of optical current and voltage sensors.<br>Aid in development of optical sensors. | EEEL | current |
| 17. | 1.2.2 | Uniform controlling software for implementation of demand-side management, FACTS systems, and remote meter reading | Harmonize control-system software systems for utilities. | EEEL, ITL | none |
| 18. | 1.5.1 | Lightning-impulse reference standard | Development of lightning-impulse standards and calibration techniques. | EEEL | current |

| | Section | Technical Needs | Implications for NIST | OU | Status |
|---|---|---|---|---|---|
| 19. | 1.5.2 | Sensors to monitor operating conditions (e.g., temperature, pressure, strain, gas composition) of power equipment (e.g., transformers and generators) to predict imminent failure, to assess *health* of device, and to determine possible failure modes | Validate, characterize, calibrate, and develop sensor performance and reliability. | EEEL, CSTL, PL | none |
| 20. | 1.5.2 | Partial-discharge (PD) detection for monitoring electrical conditions in high-voltage equipment (transformers, generators, motors, cables, etc.) | Develop measurement methods for the detection and analysis of PD signals and relate PD signatures to equipment operating conditions. | EEEL | current |
| 21. | 1.5.2 | Calibrated measurements of PD to facilitate comparisons of measurements using different PD detectors | Develop PD measurement standards and corresponding calibration techniques. | EEEL | none |
| 22. | 2.1 | Improved dynamic range for power and energy measurements to verify performance of electronic meters | Improve measurement uncertainties in power and energy calibrations to 0.01 percent. | EEEL | none |
| 23. | 2.2 | International agreements that ensure fair trade of electrical-power equipment | Ensure equivalence among international test standards (e.g., International Electrotechnical Commission (IEC)) and ensure the equitable consideration of U.S. industries in standards formulation. | EEEL | current |
| 24. | 3.1 | Clean coal-burning power plants | Develop standards for cleanliness and measurement techniques to determine efficiency cleanliness of burning process. | CSTL, PL | none |
| 25. | 3.1 | Advanced flue-gas scrubbers for power plants | Measure efficiency of effluent removal from scrubbers. | CSTL | none |
| 26. | 3.1.1 | Widely accepted standards for use of recycled $SF_6$, including levels of impurities | Determine effects of impurities in $SF_6$ and assist in development of standards for use of recycled $SF_6$. | EEEL | none |
| 27. | 3.1.1 | Environmentally friendly gaseous dielectrics for high-voltage insulation as a replacement for $SF_6$ | Verify chemical and physical characteristics of $SF_6$ substitutes under wide range of breakdown and operating conditions. | EEEL | none |
| 28. | 3.1.2 | Quick-charging, long-lasting, reliable, safe, light-weight batteries for electric vehicles and as substitutes for other uses of internal-combustion engines | Verify performance of insulation.<br>Measure battery efficiency.<br>Develop standards of safety.<br>Determine environmental effects of battery disposal. | EEEL, CSTL, MSEL | none |

| | Section | Technical Needs | Implications for NIST | OU | Status |
|---|---|---|---|---|---|
| 29. | 3.1.2 | Determination of effects of electric-vehicle proliferation on load and power quality | Validate models of load and power quality effects. | EEEL | none |
| 30. | 3.1.2 | Confirmation of safety of electric vehicles | Measure electric and magnetic fields in electric vehicles. | EEEL | none |
| 31. | 3.2 | Measurement methods to determine field strengths at the cellular levels for support of biological research | Develop methods to measure electric and magnetic fields over microscopic areas. | EEEL | none |
| 32. | 3.2 | Accurate measurements of electric and magnetic fields (EMF) for epidemiological and laboratory studies | Develop standards for EMF measurements. | EEEL | current |
| 33. | 3.2 | Validation of electrical models used to describe ion conduction at cell membranes due to field exposure | Experimental validation of these models using well-defined measurement techniques. | EEEL | current |
| 34. | 3.2 | Non-invasive technique to measure fields inside animals | Develop and validate such techniques. | EEEL | none |
| 35. | 4. | Test methods and performance criteria for equipment immunity to power-quality disturbances | Contribute to advances in the development of consensus standards and test methods. | EEEL | current |
| 36. | 4. | Compatible power-quality data recording standards | Participate in IEEE and IEC standards preparation. | EEEL | current |
| 37. | 4.1.2 | New instrumentation for characterization of surge environments in the presence of surge-protection devices (SPD) | Develop method to reliably measure current in surge events instead of surge voltage. | EEEL | current |
| 38. | 4.1.2 | Complete knowledge of failure modes of SPDs to ensure safety | Determine likely failure modes based on knowledge of surge environments. | EEEL | current |
| 39. | 4.1.3 | Reliable methods for protection of electrical transmission equipment from lightning strikes | Develop models of lightning protection effectiveness. Perform laboratory testing of lightning protection devices. | EEEL | none |
| 40. | 4.2 | Method of removing or preventing harmonic distortion of voltage and current waveforms due to non-linear loads | Determine appropriate and reasonable standards for harmonic distortion levels. | EEEL | none |
| 41. | 4.2 | Accurate metering of power in the presence of significant harmonics | Develop calibration methods to determine effects of harmonics on meter performance. | EEEL | none |
| 42. | 4.3 | Real-time independent monitoring of power system via satellite | Develop communication and data protocols. | ITL, EEEL | none |

From this list of needs, the most critical long-term needs and short-term needs *related to the transmission and distribution of electric power* have been selected for discussion in the next two sections. The selection factors considered are those contained in the Project Selection Criteria of the

Electronics and Electrical Engineering Laboratory. This is the parent organization of the Electricity Division. Special emphasis has been given to economic impact, immediacy of need, and the timeliness of NIST's possible response. The evaluation against these criteria is based on NIST's research in this area and on interactions with individuals in the electric-power industry.

Needs from Table 5 that did not make either of the following *critical* lists are also important, even if deemed of somewhat less urgency and impact at this time. Some of these are addressed by the Electricity Division for other reasons: (1) they are important to other industries, as well; (2) the Division possesses the expertise to address the particular problems effectively; and (3) the work is supportive of meeting the *critical* needs, even if not directly focused on them.

Changes in technology, in the economic environment, or in other factors can change the relative importance of the needs identified here for the electric-power industry. Therefore, continued close interaction between NIST and industry will be necessary to assure proper evolution of priorities. These interactions will be fostered through continued participation in relevant conferences, working groups, and standards bodies. Such interaction is needed not only for planning but also for delivery of NIST's findings.

## 2. CRITICAL LONG-TERM NEEDS AND NIST'S RESPONSE

The most critical long-term needs are listed in Table 6. The entries in the table are in the same order as in Table 5. Thus, while Table 6 selects out the most critical needs, the order within the table is not a priority order. The discussion that follows provides a brief summary of the importance of each of the needs. The explanation of importance, of course, is based on the discussion in Chapter One and Chapter Two. Also included is a statement of the current programs of NIST in response and of any needed additional efforts.

### 2.1 Sensors

Items 1, 3, and 4 of Table 6 are all related to the calibration and characterization of sensors for monitoring various aspects of transmission and distribution systems. This need is becoming a significant one for the utilities due to the increased demand for large-scale wheeling, the deregulation of transmission systems, and the separation of the generation function of the utilities from the transmission and distribution functions. Present NIST work is limited to developing calibration techniques for optical current sensors. Expansion is needed to include voltage sensors as well. The focus would be on developing calibration techniques for these devices, comparing their performance with more traditional voltage and current sensors, and determining parameters affecting instrument performance. Close collaboration would be needed with commercial suppliers of these sensors, and with industrial and academic researchers who are developing the next generation of sensing devices, in order to enhance the availability of devices for testing.

### 2.2 Communications Protocols

Item 2 in Table 6, related to the development of communication protocols for the utilities, is not currently being addressed by NIST, although some related work on electronic information technologies is being conducted. A new effort in this area is needed. It would focus on assisting industry in the development of standards for the communication systems used by the electric-power industry to control its systems and to interface electronically with its customers.

## 2.3 Partial-Discharge Detection

Partial-discharge detection, Item 5 in Table 6, continues to offer promise as a sensitive diagnostic tool for monitoring the integrity of insulation in cables and electrical equipment. NIST currently has a significant program in this area, funded in part by other agencies and dedicated to developing the technology and methodology for correctly monitoring and interpreting partial-discharge behavior. The emphasis of this program is, and will continue to be, the accurate measurement and analysis of partial-discharge data, with particular emphasis upon applications to cables, low-pressure dc breakdown, and partial discharges in liquids. Issues concerned with developing new or improved standards for partial-discharge measurements (both acoustic and electrical) in power systems will be addressed and will be a guiding factor in future NIST research. However, an expanded effort is this area is needed to enable faster development and transfer of detection and recording systems suitable for industrial use.

**Table 6: CRITICAL LONG-TERM NEEDS FOR TRANSMISSION AND DISTRIBUTION**

| | Technical Needs | Implications for NIST |
|---|---|---|
| 1. | Low-cost, accurate sensors for monitoring transmission systems for real-time control, for state estimation, and for monitoring monitor system disturbances (i.e., power quality) | Test, characterize, and calibrate sensor performance and reliability |
| 2. | Communication system to query and control transmission, distribution, and demand-side management-system sensors from a control center | Develop standard communication protocols and architecture. |
| 3. | Low-cost metering-grade voltage and current sensors to measure bulk power exchanges that occur during wheeling agreements and during exchanges with independent power producers | Validate, characterize, and calibrate performance and reliability of all newly introduced sensors |
| 4. | Optical current and voltage sensors as inexpensive, reliable, remote sensors | Validate stability, sensitivity, linearity, and accuracy of optical current and voltage sensors |
| 5. | Partial-discharge detection for monitoring electrical conditions in high-voltage equipment (transformers, generators, motors, cables, etc.) | Develop measurement methods for the detection and analysis of PD signals and relate PD signatures to equipment operating conditions |
| 6. | International agreements that ensure fair trade of electrical-power equipment | Ensure equivalence among international test standards (e.g., IEC) and ensure the equitable consideration of U.S. industries in standards formulation |
| 7. | Test methods and performance criteria for equipment immunity to power-quality disturbances | Contribute to advances in the development of test methods and consensus standards |
| 8. | Compatible power-quality data recording standards | Participate in IEEE and IEC standards preparation |
| 9. | New instrumentation for characterization of surge environments in the presence of surge-protection devices (SPD) | Develop method to reliably measure current in surge events instead of surge voltage |

## 2.4 International Agreements

The need for authoritative and impartial U.S. representation on committees dedicated to the formulation of international testing standards, Item 6 in Table 6, continues to grow with the increasingly global nature of the U.S. economy. NIST currently supplies representatives to three IEC committees related to the electrical-equipment industry and the electric-power industry, addressing the subjects of power quality, electric-field and magnetic-field measurements, and partial-discharge measurements. Participation in these types of international committees is important, and its continuation should be a priority. Extension of this participation to additional committees is needed, especially to include the standards committees on high-voltage measurements, power and energy metering, and transformers.

## 2.5 Power Quality

Items 7, 8, and 9 in Table 6 are all related to power-quality issues which, as discussed in Chapter Two, are becoming increasingly important for many reasons. NIST maintains a high-quality, but small, project that addresses all of these items to a degree. Many of the details of this project are defined by direct interaction with the utilities that also provide external funding.

Current NIST efforts emphasize the development of coherent national and international standards for the definition of power quality, accurate evaluation of the general power-quality environment in the United States, and the dissemination of guidelines for mitigation of poor power quality. Extension of this work is needed to enable the development of new test methods and measurement techniques that would support a truer measure of the possible effects of well-characterized power-quality variations or incidents.

# 3. CRITICAL SHORT-TERM NEEDS AND NIST'S RESPONSE

The most critical short-term needs selected from Table 5 are listed in Table 7. The treatment is similar to that above for the long-term needs. That is, the needs in Table 7 are high in priority; but the order within the table does not reflect further prioritization. The importance of the needs are summarized briefly in the terms addressed in Chapter One and Chapter Two. And NIST's current program in response is described, as well as any needed additional effort.

## 3.1 Replacement of Sulfur Hexafluoride

Item 1 of Table 7 is of immediate concern to the utilities because of the increased interest of the Environmental Protection Agency in limiting or eliminating the use of sulfur hexafluoride ($SF_6$) as an insulating gas in electrical equipment. Establishing the performance of gases that could potentially replace $SF_6$ is one of the first steps in determining the impact of $SF_6$ replacement on the electric-power industry and its supplier, the electrical-equipment manufacturers.

NIST's past program in this area, completed in FY 1995, focused on the characterization of electrical breakdown in $SF_6$. NIST's current program in this area is directed at reviewing the available data to identify the gases that are most promising as substitutes for $SF_6$ in high-voltage equipment. An expansion of this program is needed to permit the testing, and thus the validation, of the most promising substitute gases.

**Table 7: CRITICAL SHORT-TERM NEEDS FOR TRANSMISSION AND DISTRIBUTION**

| | Technical Needs | Implications for NIST |
|---|---|---|
| 1. | Environmentally friendly gaseous dielectrics for high voltage insulation as a replacement for $SF_6$ | Verify chemical and physical characteristics of $SF_6$-substitutes under wide range of breakdown and operating conditions. |
| 2. | Accurate measurements of electric and magnetic fields (EMF) for epidemiological and laboratory studies | Develop IEEE and IEC standards for EMF measurements. |
| 3. | Accurate metering of power in the presence of significant harmonics | Develop calibration methods to determine effects of harmonics on meter performance. |

## 3.2 Electric and Magnetic Field Measurements

Concern about exposure to electric and magnetic fields, in Item 2 of Table 7, has decreased recently, due to a new report of the National Research Council [170]. However, many questions regarding the possible health risks of exposure remain unanswered. Reliable measurements of the exposure fields will continue to be critical to studies that will address these questions.

NIST currently maintains a program dedicated to the maintenance and dissemination of reliable techniques for the measurement of electric and magnetic fields in support of biological field-effect studies. This program is the leading effort to develop national and international standards for field measurements. The completion of these standards is an important short-term need. NIST expects to continue current research activities (funded in part by DOE) into at least the near future. However, further support, if available, would be used first to extend field measurements into biological systems. Also, efforts to address other measurement needs related to electromagnetic fields (Items 28 to 32 of Table 5) are needed.

## 3.3 Accurate Revenue Metering in the Presence of Harmonics

The problem of high-frequency harmonics on the power lines, noted in Item 3 of Table 7, arises primarily from the increased use of switching power supplies in end-use equipment. These higher frequencies can disturb the accurate revenue metering of electric power, particularly in three-phase systems. NIST presently has no effort dedicated to measuring the effects of higher harmonics on power and energy measurements. New work is needed to address this problem. This topic is made all the more important by the emergence of new electronic watt-hour meters that respond to the higher frequencies. Specifically needed is determination of the true performance of revenue meters in the presence of harmonics and translation of that performance into its effects on the electric-power industry and its customers. Then, if found necessary, new measurement solutions will have to be pursued.

# 4. CLOSING OBSERVATIONS

This analysis indicates that the major changes taking place in the U.S. electric-power industry are giving rise to a broadened spectrum of measurement needs related to the transmission and distribution of electric power. Many of these needs are already being addressed by NIST, and NIST's findings will have a major impact on the industry. Many more needs remain to be addressed. The shortfall is not surprising given the tremendous size of this industry. Increased resources -- should they become available in the future -- can be applied effectively to the critical needs identified here. Addressing these will have a major impact on the U.S. economy through the pervasive role that the cost, reliability, and versatility of electricity play in the national infrastructure.

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