Transmission and Distribution Technologies Program Overview FY 1993–FY 1994

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Cover photos—Left: Energy control center, Florida Power Corporation.
Right: Six-phase transmission towers, Oak Ridge National Laboratory.

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Acronyms and Abbreviations

AC	alternating current
AEP	American Electric Power Company
APPA	American Public Power Association
BPA	Bonneville Power Administration
CRADA	cooperative research and development agreement
DC	direct current
DOE	U.S. Department of Energy
EEI	Edison Electric Institute
EMI	electromagnetic interference
EMP	electromagnetic pulse
EPACT	Energy Policy Act of 1992
EPRI	Electric Power Research Institute
FACTS	Flexible Alternating Current Transmission Systems
FY	fiscal year
GDP	gross domestic product
GIC	geomagnetic induced current
GW	gigawatts
HVDC	high-voltage direct current
Hz	hertz
JPL	Jet Propulsion Laboratory
km	kilometer
NEMA	National Electrical Manufacturers Association
NYSE&G	New York State Electric and Gas Corporation
NYSERDA	New York State Energy Research and Development Administration
ORNL	Oak Ridge National Laboratory
R&D	research and development
RTSC	real-time system control
T&D	transmission and distribution
V _{LL}	Line-to-line voltage
V _{LN}	Line-to-neutral voltage
WAPA	Western Area Power Administration

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Introduction

Electricity is the lifeblood of our Nation's economy and a critical contributor to our standard of living. For decades, increases in the gross domestic product (GDP) have been accompanied by increases in electricity use. A growing reliance on electrotechnologies, such as computers, other new information and communication technologies, and electrical industrial processes, is expected to increase dependence on electric energy and high levels of power quality into the future. The projected electricity consumption to 2010 parallels the growth in GDP and significantly exceeds the growth in total energy consumption (Figure 1). The backbone of the Nation's electricity network, the transmission and distribution (T&D) infrastructure, must accommodate this growing need for electricity. Meeting this demand at the least cost will present a formidable challenge.

This overview provides the reader with an introduction to the U.S. Department of Energy's (DOE's) T&D Technologies Program. It shows how the program is meeting the challenges being imposed on the T&D infrastructure by the changing electric power industry and how the Nation will benefit from its efforts. The overview describes the program's ongoing projects and discusses the new projects being initiated in fiscal year (FY) 1995.

The U.S. T&D network has become one of the most complex systems ever built. Today, the system consists of millions of miles of wire and millions of transformers, switches, protection devices, meters, insulators, and poles. Even if demand were not growing, customer expectations regarding power quality are continually increasing, and aging equipment must be continually replaced. Demand, however, is increasing, and utilities must upgrade the T&D system to cost effectively meet load growth as well as customer needs and expectations. The technical

Warren Greiz, National Renewable Energy Laboratory

The U.S. T&D system has grown into a complex network containing millions of miles of wire and millions of transformers, switches, protection devices, meters, insulators, and poles.

Sources: Annual Energy Review 1992, DOE Energy Information Administration, pp. 25, 215
Annual Energy Outlook 1994, DOE Energy Information Administration, pp. 55, 65, 75

Figure 1. Comparison of energy, electricity, and economic growth

Mission

The mission of DOE's T&D research is to develop and demonstrate technologies that increase the flexibility, capacity, and efficiency of the U.S. T&D system in order to enable potential alternative future electric markets. This will promote optimal use of renewable resources, energy storage, integrated resource planning, energy efficiency measures, and competitive electric markets.

challenges of upgrading such a large and complex system are formidable.

Adding to these technical complications is a changing business environment for generating and distributing electricity. A whole new class of nonutility generation enterprises is marketing power, open transmission access is a reality under the Energy Policy Act of 1992 (EPACT), and the possibility of enabling competition for other utilities' customers (known as "retail wheeling") has been proposed by at least three states (California, Michigan, and Nevada). This growing competition increases the number of buyers and sellers, complicates the way energy transactions are monitored and controlled, and places new demands on the T&D infrastructure.

In addition, utilities are exploring renewable resources, including solar, wind, and geothermal energy, and energy storage systems. These resources have different operating characteristics and requirements than do conventional utility power systems; therefore, full implementation of renewable sources and energy storage systems will require changes in the T&D system.

Finally, despite growing demand, utilities find it increasingly difficult to obtain approval to build new generation capacity, new T&D lines, and new substations. Public opposition (based on such concerns as environmental aesthetics and the potential health effects of electric and magnetic fields) constrains T&D options. Utilities will need flexible options to meet additional requirements.

These trends will require utilities to develop a modern power system that uses advanced power electronics, enhanced computer and communication systems, new sensors, and smart interactive utility/customer interface systems. This intelligent power system will increase system efficiency, optimize use of utility assets, increase the incorporation of renewables, and increase system capabilities while maintaining or improving customer reliability. In addition, this intelligent system will improve service and reduce detrimental effects on the environment while saving the utilities and their customers billions of dollars annually.

DOE recognizes the need for a more robust, modern T&D network for the future. Through its T&D Technologies Program, DOE is a catalyst in developing new technologies to create an intelligent power system, which will enable optimal use of renewable resources, energy storage, integrated resource planning, and energy efficiency measures. The overall goal of the Federal T&D Technologies Program is to consider the trends that affect electric utilities and support research and development (R&D) activities that develop the T&D infrastructure for the 21st century.

R&D Opportunities Based on National Trends

The T&D Program's R&D activities focus on developing a national T&D network that can accommodate growing:

- Competition
- Need for generation, transmission, and distribution capacity
- Change in generation mix
- Need for enhanced electrical services, such as high levels of power quality.

The T&D Technologies Program develops products to help utilities respond to these trends. The program focuses on two advanced technology areas: real-time system control (RTSC) and high-capacity transmission. A third program area, advanced systems analysis, is being initiated in FY 1995.

Competition

To meet the demands created by utility competition and the growth of nonutility generators, the T&D network must control costs while accommodating greater wholesale and, potentially, retail wheeling. Utilities will need advanced communications and sensing networks, data management techniques, and control technologies provided by RTSC to maintain high reliability. Also, RTSC will allow utilities to input contractual agreements for buying power from various producers, monitor power flows for

Florida Power Corporation

Advanced communications and sensing networks will allow utilities to maintain high reliability in the face of increasing demand, competition, and changes in the power generation mix.

individual customers in real time, monitor power produced at generators, and meter delivered power from other utilities or nonutility generators carried on the utility's transmission lines. In addition to RTSC, high-capacity transmission options will enable utilities to handle wholesale and retail wheeling of power. These technologies will help utilities increase the power-handling capability of existing and new transmission lines.

Need for Generation, Transmission, and Distribution Capacity

In order to meet projected increases in electrical demand, the United States will need an additional 115 gigawatts (GW) of new generation capacity by 2010 and 100,000 circuit miles (160,000 circuit kilometers [km]) of new T&D lines (22-kilovolt and above) at a cost of around

\$135 billion.^{1,2} To assist in meeting this demand at the lowest capital cost, the T&D Program is developing technologies to help utilities use their existing assets more efficiently. Through a combination of advanced sensors, power electronic controls, communication systems, and control algorithms on the T&D network, RTSC will enable utilities to operate the transmission system closer to its thermal and stability limits, allowing the existing system to carry higher power flows. High-capacity transmission will allow utilities to transmit more electricity through new lines over existing rights-of-way and reduce the projected 100,000 circuit miles (160,000 circuit km) of transmission lines needed for future growth.

Change in Generation Mix

As load growth has slowed and natural gas has become more available, the economies of scale of very large central station power plants have become more difficult to realize. Thus, some utilities have started to consider small generation plants, including renewable plants, and energy-storage systems for sites at the distribution level. For these approaches to work most effectively, utilities will need the monitoring and control at the distribution level that RTSC can provide.

Because the output of solar and wind plants is variable in somewhat unpredictable ways, a utility with renewable generation comprising more than approximately 10% of the generation mix may require increased reserve margins. Working together, utilities, solar and wind systems manufacturers, and the DOE T&D Program can develop advanced technologies that help realize the full potential energy contribution from renewable energy sources.

Many of the best renewable sites are located far from the load centers. Utilities will need high-capacity transmission technology to increase the power-handling capability of existing rights-of-way and to provide inexpensive options for new transmission lines to carry the power economically from remote sites to the cities. In some cases, transmission lines of 300 to 800 miles (480 to 1290 km) will be required to transmit power to load centers.

¹ *Annual Energy Outlook 1994*, p. 66.

² *Statistical Yearbook of the Electric Utility Industry*, Edison Electric Institute, 1992 and previous years, Tables 1 and 86.

Technical Program Elements

Real-Time System Control

In the present utility network (Figure 2), the utilities monitor and control their generators and have some monitoring and control of transmission lines and substations. However, utilities have very little monitoring or control of the distribution network. In fact, a utility may not know the extent or location of a blackout until customers call to report power outages. Also, because disturbances on the electric network grow faster than human operators can react, today's system relies on system inertia, extra capacity, and

preset protective devices to handle disturbances.

Full implementation of RTSC will create a much more sophisticated utility network with monitoring and control at generation, transmission, distribution, and end-use points (Figure 3). "Real time" has three distinct time frames: within 1 cycle (1/60th of a second) to respond to T&D disturbances, from 1 to 10 seconds for area control information such as load or generator output, and from 5 to 15 minutes for exchanges of information between the utility and customers.

Figure 2. Control in today's utility network

Figure 3. Control in tomorrow's utility network

With RTSC, the utility can make control decisions based on sensor data by using computer networks, control algorithms, and artificial intelligence, combined with flexible alternating current (AC) transmission devices to reroute power. These RTSC systems will automatically maintain safe, stable operating conditions under normal circumstances and deal with disturbances as they occur.

Under RTSC, the human operator will gather status and supervisory information from the control network. Under normal circumstances,

however, the operator will not have to intervene and control the network. This hierarchy of distributed controllers, each passing only the most important data to the next level, will oversee the electric network.

High-Capacity T&D Options

High-Phase-Order Alternating Current Transmission

For the most part, electricity is transmitted by three-phase systems. This means that power is divided among three wires or phases. The

voltage of each phase is displaced with respect to the other two phases by a time period of one-third of a cycle. Theoretically, the potential number of time-displaced phases has no limit. Systems with more than three phases are referred to as high-phase-order systems.

Six-phase systems have phases one-sixth of a cycle apart. Twelve-phase systems have phases that are one-twelfth of a cycle apart. Figure 4 depicts three-, six-, and twelve-phase systems. Because adjacent wires are only slightly different in phase, high-phase-order systems have lower line-to-line voltage (V_{LL}) than do three-phase systems with the same line-to-neutral voltage (V_{LN}). For six-phase systems, V_{LL} equals V_{LN} . Systems with more than three phases offer significant benefits. A six-phase system can occupy the same space and transmit twice as much power as a three-phase system with the same V_{LN} . Also, both the circular pattern and the smaller line spacing reduce the magnetic field at the edge of the right-of-way of a high-phase-order line compared to that of a three-phase line.

High-Voltage Direct Current Transmission

Most of the electric power generated and transmitted in the United States is AC power. AC has been the technology of choice for nearly 100 years because transformers can easily change AC voltage levels.

Six-phase transmission towers allow high-phase-order systems to transmit twice the power of conventional three-phase systems within the same space.

Bonneville Power Administration (BPA) installed the first commercial U.S. high-voltage direct current (HVDC) system in 1969 to transmit power more economically over the

Figure 4. Three-phase and high-phase-order systems

Oak Ridge National Laboratory

Celilo substation, part of the Bonneville Power Administration's high-voltage direct current system, uses solid-state switches to transform current from alternating to direct and from direct to alternating.

long distance from the Pacific Northwest to load centers in Southern California. The original system used mercury-arc valves to transform the AC to DC and the DC to AC. Upgrades use solid-state switches called thyristors.

HVDC transmission offers several advantages over high-voltage AC transmission. HVDC can transmit power over long distances by overhead lines or underground cable without the large and expensive voltage control equipment required for long-distance AC transmission. HVDC can also transmit power between AC networks that cannot otherwise be connected, permitting power sales and purchases in a controllable fashion between such asynchronous systems.

HVDC lines use rights-of-way more efficiently than AC lines by transmitting almost four times as much power through the same corridor. Finally, HVDC lines do not cause 60-hertz electric and magnetic fields.

HVDC shares an additional advantage with the Electric Power Research Institute (EPRI)-developed Flexible AC Transmission Systems (FACTS) technology. This is the ability to control power flows more precisely. Power flow division in a traditional AC network is uncontrolled, and power divides between the lines of the network based on system impedances. Both HVDC and FACTS devices have the ability to control power flow allowing routing around AC system bottlenecks. Both HVDC and FACTS make use of the

same solid-state power electronics building blocks.

National Impacts

DOE is committed to safe, economical, and efficient National energy production, delivery, and use. The T&D Technologies Program's results in both RTSC and high-capacity transmission contribute to this goal across a range of utility situations. Utilities in slow-growing areas with stable energy resources benefit the most from the RTSC program to defer capital expansion and extend the life of existing equipment. Utilities in fast-growing areas, or with aggressive resource expansion plans for renewable or other remote generation, benefit from development of low-cost, high-capacity transmission options, as will urban utilities facing right-of-way expansion limitations.

The enhancement of electric utility competitiveness that is expected to result from RTSC and high-capacity transmission will have a positive impact on the Nation's economy. T&D Program results will allow utilities to deliver more energy at lower cost while maintaining high reliability. New technologies, developed through collaborative efforts with private industry, will help U.S. electric power equipment manufacturers become more competitive both nationally and internationally. Full implementation of the results of the T&D Program will save utilities, their customers, and the Nation billions of dollars annually by reducing capacity margins, enabling the T&D system to provide the

benefits of increased competition, and promoting cost-effective integration of renewables.

The implementation of RTSC could result in cumulative savings of more than \$12 billion because of deferred investments by 2020. This would occur if generation reserve margins were reduced by 2% of the total generating capacity, and if this were accompanied by a corresponding 20% decrease in reserve margin-induced new transmission construction. Similarly, if only 12% of the potential market for new transmission construction were captured by HVDC with its higher capacity per mile of line, the resulting reduction of 12,000 miles (19,000 km) of new conventional transmission construction would be reflected in an additional cumulative savings of more than \$2 billion. If RTSC advances in transaction systems enabled competitive forces to lower energy costs by only 2 mills per kilowatt-hour, the result would be an annual savings of more than \$8 billion. Finally, if HVDC advances led to increased renewables penetration at a level of 15 GW, the annual savings would total an additional \$0.5 billion.

Oak Ridge National Laboratory

T&D Program results will allow utilities to deliver more energy at a lower cost while maintaining high reliability.

FY 1993 and FY 1994 Accomplishments

Real-Time System Control

The RTSC initiative began with a meeting of about 70 nationally and internationally recognized experts

from utilities, industry, academia, and government who helped DOE set research goals and objectives and identified the most cost-effective R&D paths. DOE and Oak Ridge National Laboratory (ORNL) continuously refine the goals and objectives of the original RTSC initiative by analyzing the market and emerging technologies. The RTSC Technical Committee provides input to this process.

In FY 1993, the T&D Program completed two tasks related to RTSC with the Virginia Polytechnic Institute and State University. For the first task, researchers developed an application of real-time phasor measurement techniques for on-line monitoring and control of power systems. The researchers advanced the theoretical basis of this approach to power system control and confirmed the approach with simulation studies of realistic system configurations.

On the second task, the researchers performed a study of power system relays during blackouts, gained a better understanding of power system blackouts, and developed strategies to monitor and control protective relay systems to reduce blackout occurrences. They investigated failures from damaged or defective protective relays that remained undetected on the network. The researchers also defined regions of vulnerability based on

T&D Technologies Program—Significant Events

Six-Phase Demonstration Project

From 1976 to 1985, DOE funded a feasibility study on high-phase-order transmission. In 1985, Empire State Electric Energy Research Corporation (ESEERCO) and the New York State Energy Research and Development Administration (NYSERDA) joined DOE in funding the electrical testing to complete the twelve-phase experimental program.

In 1985, ESEERCO, NYSERDA, DOE, the Electric Power Research Institute, New York State Energy Office, and New York State Electric and Gas Corporation (NYSE&G) agreed to undertake a joint demonstration project to build the world's first six-phase transmission line. NYSE&G chose one of its double-circuit, three-phase lines for conversion to six-phase operation.

The project's purpose is to demonstrate and analyze the performance of high-phase-order transmission on a utility electric grid. Line design and construction occurred between May 1990 and July 1992. In July 1992, the six-phase line was energized and will be operated and tested until July 1995, when it will be decommissioned and returned to its original state.

AbNET Communications System Demonstration Project

The AbNET communications system was developed at NASA's Jet Propulsion Laboratory (JPL) with DOE funding specifically for utility use. In November 1992, LICOM, a communications equipment manufacturer based in Herndon, Virginia, bought a license to use the AbNET technology. Next, JPL and American Electric Power (AEP) contracted to perform a demonstration. In March 1994, LICOM prototype components were installed at the AEP Ohio facility. In June 1994, new monitoring and control software, written by JPL, was sent to the AEP facility. The AEP-funded demonstration is scheduled to last 1 year.

AbNET is a fiber-optic network designed specifically for utilities. It features a high degree of fault tolerance; the normal high bandwidth of fiber systems has been traded off in favor of more robust operation. The system is nevertheless fast enough to poll a 100-node system for data in less than 3 seconds, a typical scan rate for supervisory control and data acquisition. In operation, AbNET uses the master/slave hierarchy typical of utility data acquisition systems to control access to the network, and it floods the network with copies of messages in such a way that all possible routes between source and destination are explored.

operating criteria in which an event could activate a hidden failure and cause large outages.

The T&D Program funded research at the Jet Propulsion Laboratory (JPL) on utility fiber-optic communication systems and on utility applications of neural networks related to RTSC. The communication project involves a partnership among JPL; American Electric Power Company (AEP), a utility; and LICOM, a manufacturer of fiber-optic communications systems. In FY 1993, JPL assisted with the installation of its first demonstration system at AEP and began testing. The demonstration system used PC-based computers, fiber optics, and communication protocols developed by JPL to model a utility supervisory control and data acquisition system.

In a separate effort with the T&D Program, JPL is investigating applications of neural networks to improve the control of power system stabilizers. Neural networks can control real systems well because neural networks emulate human thought processes and can be "trained" to sort important information from ambiguous background.

In response to the Telephone Disclosure and Dispute Resolution Act, DOE and the Department of Commerce submitted a report to Congress that contained the required proposal for a demonstration of new and innovative utility communications systems. The systems would have the capability to remotely read utility meters, manage the consumption of electricity

Additional T&D Program Highlights

FY 1993

Produced statement of work for R&D projects on real-time system control of electric power networks.

Completed assessment of anatomy of power system blackouts and preventive strategies.

Completed a development plan for high-power switching devices for high-voltage direct current applications.

Completed analysis of the integration of renewable generation into the electric power distribution network.

Began a study of transmission requirements of renewable generation located remotely from load centers.

Installed geomagnetic disturbance monitor at Oak Ridge National Laboratory.

Developed model for solar storm analysis.

Published first newsletter on S_2F_{10} detection, production, and mitigation.

FY 1994

Request for proposals for real-time system control released.

Request for proposals for high-voltage direct current initiative released.

Jet Propulsion Laboratory demonstration of AbNET completed.

Patent disclosures on three voltage source-converter configurations submitted.

Studies on two renewable energy integration projects completed.

Report on upgrading distribution transformers during routine maintenance completed.

Oak Ridge National Laboratory and Jet Propulsion Laboratory began applying artificial intelligence approaches to T&D control algorithms.

and natural gas by residences and businesses, and monitor utility outages. Using information provided by stakeholders through a Notice of Inquiry in the Federal Register and information available in the trade press, the report assessed key issues and the status of actions by utilities to demonstrate these systems. Because numerous utilities were already demonstrating these systems, the report recommended

that Federal funds not be appropriated for this demonstration.

As the next step for the RTSC initiative, ORNL released requests for proposals covering four areas: distribution control combined with measurement and sensor technology, voltage dynamics, data calibration, and regional power transfers.

High-Voltage Direct Current Transmission

In 1992, the T&D Program assembled a group of experts from industry, academia, utilities, and the public sector to assist DOE in setting research priorities and determining the best research areas for the HVDC initiative. This HVDC Technical Committee provides continuing guidance to DOE and ORNL on HVDC research.

DOE and ORNL prepared an R&D plan to reduce HVDC equipment costs by 40% to 50% during the next 10 to 15 years. HVDC transmission lines are less expensive to build than are AC lines at similar voltages. However, the cost of an AC/DC converter at each end of the HVDC transmission line means that HVDC is only cost effective for lines longer than 400 miles (645 km). Reducing converter costs by 50% will make DC lines as short as 150 miles (240 km) in length economically attractive.

ORNL has started three investigations to lower AC/DC converter costs. The first investigation is of converter configurations that use controllable, turn-off devices to improve performance and reduce

cost by eliminating ancillary equipment such as transformers and filters. ORNL is also investigating higher power thyristors made from silicon carbide instead of the standard silicon. In the third investigation, ORNL is evaluating high-voltage switches that use gas and liquid switching media. By using higher voltage switches, manufacturers can build higher power converters at a lower cost per watt.

High-Phase-Order Transmission

Since July 1992, the T&D Program has successfully operated the world's first six-phase transmission line at New York State Electric and Gas Corporation. The six-phase line was built as a retrofit of a double three-phase line. Operational tests continued in FY 1993 and will continue until the end of the project in FY 1995, when the line will be returned to its original configuration. This project has shown that a six-phase line can be successfully integrated into a utility T&D network.

Renewable Energy Integration into the T&D Networks

As directed by Congress, the DOE T&D Program began two studies on renewable energy integration in FY 1993. The first study examined the possibility of locating small-scale solar and wind generators on distribution systems as a means of deferring transmission system capital investment and reducing the

need for fossil-fueled central station peaking generators. Case studies at seven utilities examined the costs and benefits for specific applications, and a national overview extended the results. The study showed that, although solar photovoltaic installations provided an acceptable means of reducing commercial load peaks in high resource areas, costs are still approximately twice as high as benefits. Wind turbine installations, on the other hand, had much more limited applicability; however, where appropriate, they showed benefit-to-cost ratios in excess of 1:1.

In the second study, ORNL worked with utilities and representatives of the wind and solar energy industries to examine the transmission capacity requirements for integration of relatively large-scale wind and solar resources (25 megawatts or more). This study was also based on case studies performed by cooperating utilities and includes an analysis of 11 proposed generation sites. The case studies were completed in FY 1994.

Distribution Transformer Efficiency

In response to EPACT, DOE asked ORNL to evaluate the practicality, cost-effectiveness, and potential energy savings of upgrading or replacing existing utility distribution transformers during routine maintenance prior to the end of their normal service lives. In FY 1993, ORNL began the study by

developing survey forms that were distributed by the Edison Electric Institute (EEI) and the American Public Power Association (APPA) to determine maintenance practices and loss evaluation factors. Manufacturers were also polled through the National Electrical Manufacturers Association (NEMA) to determine composite sales volumes, costs, and performance of transformers.

A second study to determine the economic justification and technical feasibility of efficiency standards for new distribution transformers, both utility and nonutility owned, was mandated by EPACT. The T&D Program is working closely with the DOE Office of Building Technologies, which is sponsoring this study. Additional data will be obtained from NEMA covering the cost and performance of the dry-type transformers typical of commercial and industrial applications. Users and trade associations will also be asked to provide information on loading practices and purchase evaluation factors. Both studies continued in FY 1994.

This effort is part of Action 29 of the Energy Partnership for a Strong Economy. Action 29 is intended to accelerate the standards determination and standards implementation processes for distribution transformers, if warranted, as prescribed in Section 124 of EPACT.

Oak Ridge National Laboratory

A geomagnetic disturbance monitor at Oak Ridge National Laboratory, along with data from the U.S. Geological Survey and the Electric Power Research Institute, is being used to characterize severe solar storms and their impact on the T&D system.

David Parsons, National Renewable Energy Laboratory

T&D Program research on lightning's effect on the utility grid provides information on lightning-induced voltages and determines the effectiveness of lightning protection measures.

ORNL completed the analysis for the replacement versus refurbishment study; the analysis for the standards determination is under way. Both efforts on distribution transformer efficiency continued in FY 1994.

Power Transients

During the past decade, the T&D Program has made a large effort to assess the effects of power transients, which are short-duration disturbances of the electric network. The transients include geomagnetic disturbances, lightning, electromagnetic pulses (EMP), and electromagnetic interference (EMI).

In FY 1993, the T&D Program installed a geomagnetic disturbance monitor at ORNL. Data from this monitor will be used along with data from U.S. Geological Survey and EPRI monitoring sites to characterize severe solar storms and their impact on the T&D system. Solar storms interact with Earth's magnetic field and cause voltage gradients at the Earth's surface, particularly in northern latitudes. The voltage gradients cause quasi-DC currents, known as geomagnetic-induced currents (GIC), to flow in power systems with grounded neutrals. GICs can affect transformers and protective relays and cause power outages. In FY 1993, the T&D Program also developed a model of a power transformer subjected to GICs to help develop recommendations for improved transformer arrangements.

In FY 1993, the T&D Program neared completion on the studies of lightning effects and mitigation techniques. Research sponsored by the T&D Program over the past decade has helped to improve the understanding of lightning interactions with the utility grid. Data on the effects of near and distant lightning on an unenergized distribution line supported modeling of lightning-induced voltages on a power line, determined the applicability of available computer codes for calculating lightning-induced voltages, and determined the effectiveness of current lightning protection measures.

In FY 1993, the T&D Program finished its study of the effects of EMP and EMI on electric power systems.

The research helped to achieve a better understanding of EMP/EMI interactions with the utility network and to develop operational procedures, technologies, and standards to enhance the reliability of the T&D network when subjected to EMP/EMI.

The results of program efforts on transients from geomagnetic storms, lightning, and EMP/EMI have been reported to utilities, industry, and U.S. and international standards organizations.

S₂F₁₀ Research

Utilities use sulfur hexafluoride (SF₆) gas to electrically insulate high-voltage components. Electrical discharges in SF₆-insulated equipment can form toxic S₂F₁₀ and other potentially toxic by-products. Therefore, utilities need to understand how S₂F₁₀ forms and decomposes, and how to detect S₂F₁₀ at very low concentrations. The federal safety limit on S₂F₁₀ is 10 parts per billion for a one-time exposure.

To meet these utility needs, the T&D Program formed a cooperative research and development agreement (CRADA) to address detection, formation, decomposition, and toxicity issues, and to disseminate information about S₂F₁₀. The CRADA members are DOE, ORNL, the National Institute of Science and Technology, Ontario Hydro, EPRI, BPA, the Canadian Electrical Association, Empire State Electric

Energy Research Corporation, the Tennessee Valley Authority, and Hydro-Quebec.

This CRADA developed two detection methods that can measure 10 parts per billion S₂F₁₀ in SF₆. Both techniques were used to measure S₂F₁₀ samples from the CRADA members. Research also included laboratory experiments to measure the S₂F₁₀ production from various types of electrical discharges. The program funded research on mammalian cell cultures to study toxicity and ways to reduce it. To transfer research results to industry, the T&D Program published the first Technical Note on S₂F₁₀ in FY 1993. The CRADA team on S₂F₁₀ is expected to complete its research in 1994.

Oak Ridge National Laboratory

T&D Program researchers are using mammalian cell cultures to study the toxicity of S₂F₁₀—a by product of the gas SF₆ that is used to electrically insulate high-voltage components.

Future Program Activities

Future activities in the T&D Program will focus on three program areas:

Real-Time System Control

The program will seek to develop T&D system control algorithms using artificial intelligence approaches. In addition, field trials of a Wide Area Measurement system using satellite clocks to synchronize collected data will be developed together with the Western Area Power Administration (WAPA) and BPA. The system will be installed in the WAPA service area during 1995 and will be used to assess methods for controlling large-system phenomena such as loop flow and voltage instabilities.

High-Capacity Transmission Options

Work will continue on development of voltage-source converter topologies. Possible applications issues will be simulated, and cost modeling will determine whether the additional capabilities offered by voltage-source converters can be implemented at an attractive cost.

Work will also continue on fabrication of device-grade silicon carbide, a prime contender for the base material of the next generation of high-power switching devices. An evaluation of the potential for

development of gas switching devices will be completed. It is possible that high-speed gas switches developed for the Strategic Defense Initiative can be optimized for the more prosaic application of an HVDC converter switch.

Advanced Systems Analysis

A new program area will be launched in FY 1995. It will develop power system modeling techniques required by the power systems of the future, which are expected to be actively controlled in real time. In addition, this program area will use system performance analyses to support the integration of advanced technologies of various types, from superconducting magnetic energy storage devices to fault current limiters. Standard power system modeling tools such as power flow, transient analysis, and production costing, as well as special-purpose, custom-developed models, will identify system interactions, control needs, and opportunities.

Program Management

The T&D Program manager at DOE Headquarters in Washington, D.C., directs program activities and allocates resources. ORNL implements the activities of the program to achieve goals and milestones, supervises R&D contracts, disseminates research results, and transfers technology to industry. ORNL also works with DOE Headquarters to coordinate research with stakeholders, including utilities, the Power Marketing Administrations, EPRI, the National Rural Electric Cooperative Association, EEL, APPA, manufacturers, and universities.

JPL performs work under the direction of the DOE T&D Program manager. It also coordinates closely with ORNL on developing technologies for the enhancement of utility control and communications for electric power systems.

The T&D Program receives guidance and input from the executive-level T&D Steering Committee, a group that is chaired by DOE and comprised of representatives from the Power Marketing Administrations, utilities, EPRI, and ORNL. The committee meets annually to discuss current research activities and specific program agendas. Two separate technical committees comprised of senior-level engineers and managers provide input on RTSC and HVDC transmission.

Coordination

The T&D Program works closely with several other DOE programs to exchange technical information and results, coordinate activities, and support integration of new technologies into the existing National energy infrastructure. For example, the T&D Program coordinates with the Electric and Magnetic Field Effects Program, the Superconductivity Program for Electric Power Systems, the Utility Battery Storage Systems Program, and renewable energy programs in the Office of Utility Technologies.

In addition to coordinating with existing DOE programs, the T&D Program may become an integral part of Vice President Gore's emerging National Information Infrastructure Initiative. The T&D Program's goals are parallel to the initiative's goal of fostering relationships between energy, telecommunications, and computer industries to create a national information superhighway.

The T&D Program also coordinates work with EPRI, the research arm of the electric utility industry. Research efforts of the T&D Program and EPRI are complementary and supportive.

Steering Committee Functions

- Provides input into multiyear planning and direction of T&D Program
- Evaluates progress in implementation of program activities and recommends changes in planning and implementation
- Provides guidance and recommendations on DOE positions and potential agreements with external organizations
- Establishes technical advisory panels, as needed, to provide input from and assist in coordination with utilities, manufacturers, universities, and other organizations.

Steering Committee Members

- Department of Energy
- Bonneville Power Administration
- Western Area Power Administration
- Electric Power Research Institute
- Oak Ridge National Laboratory

Industry Participation

The participation of private industry as a partner in R&D builds on the capabilities of the National Laboratories, provides focus to the research agenda, and enables the rapid transfer of commercially valuable technology to the marketplace.

DOE funds most of the exploratory phase of the research. As the work progresses, the T&D Program pursues both applications development and demonstration partnerships to transfer research products to industry and speed commercialization of T&D technology. Applications development focuses on cost-shared work and other means to involve manufacturers in the development of commercially viable products. Demonstration partnerships work with vertically integrated teams. At a minimum, these teams are composed of a manufacturer and a utility. For some project areas, an end-user group is added to the team. The objective is to demonstrate a cost-effective application of the technology under development.

Program Managers

Robert Brewer
Director
Utility Systems Division, EE-141
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 586-2206

Philip Overholt
T&D Program Manager
Utility Systems Division, EE-141
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 586-8110

Susan Rogers
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 586-8997

Roland George
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
(202) 586-9398

James VanCoevering
Manager, Power Systems
Technology Program
Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831-6070
(615) 574-4829

For additional information, or for copies of reports published as part of the T&D Technologies Program, contact Mr. Philip Overholt at the above address.