Inaugural IEEE PES 2005 Conference and Exposition in Africa
Durban, South Africa, 11-15 July 2005

Overview of Transmission Lines Above 700 kV

Raymond Lings
Transmission & Distribution, Power Delivery & Markets
EPRI, 3412 Hillview Avenue, Palo Alto, California 94304 USA
Phone 650/855-2177
Vernon Chartier
P. Sarma Maruvada

***Abstract*—This paper describes the transmission lines that have been built throughout the world to operate above 700 kV. The paper provides information on the system planning, the electrical design, the mechanical and tower design, and the operation and maintenance experience of lines built in the U.S., Canada, South Africa, Brazil, Venezuela, Russia, Korea, India and Japan. Also briefly discussed is the research conducted around the world to develop systems to operate above 700 kV including the research conducted by EPRI at their high-voltage research facility in Lenox, Massachusetts.**

I. Introduction

Once high-voltage ac power transmission became feasible in the early twentieth century, there arose a continuing trend toward the use of increasingly higher voltages for transmitting large blocks of power efficiently over long distances. Higher-voltage transmission lines were also essential for the development of large interconnected power networks, one of the most important engineering achievements of the twentieth century.

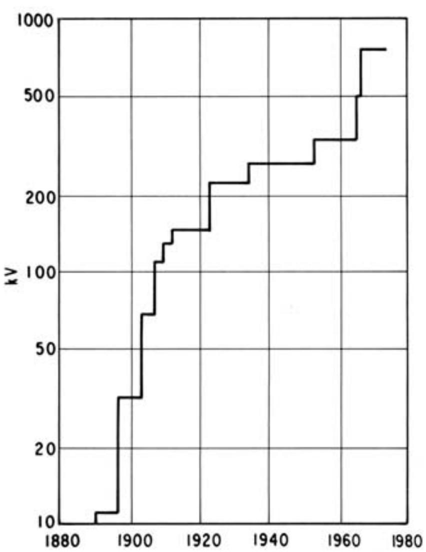

Fig. 1 Highest ac transmission voltages in North America (EPRI 1982).

Since the mid-1960s, transmission lines in the range of 700-800 kV were designed, built, and operated in several countries. Some of these lines have been in operation for 20-40 years, while others have been built more recently and in operation for only a few years. There are indications that more transmission lines will be constructed in the 700--800 kV range in many countries, and consequently, there is a need for information on the experience so far on the design, construction, operation, and maintenance aspects of lines at voltages above 700 kV. The main objective of this paper, therefore, is to provide a summary of the relevant experience of utilities in different countries that have transmission lines above 700 kV.

The first 735-kV transmission lines were built by Hydro-Québec in 1965. Although efforts continued to establish the technical feasibility of power transmission in the range of 1000-1500 kV, practical implementation of transmission systems at these voltages was not feasible because of a steady decline in load growth following the energy crisis that began in 1973. Transmission lines in the range of 1000-1200 kV were built in Russia (the former USSR) and Japan, but the Russian line, after a few years of operation at the design voltage of 1150 kV, has been operated at the lower level of 500 kV, while the Japanese 1000-kV line has been operated since it was built also at 500 kV. Thus, the highest operating transmission voltage in different countries around the world continues to be in the range of 700-800 kV.

A preliminary survey identified nine cases of transmission lines in the 700-800 kV range—in Canada, United States, Brazil, Venezuela, Russia, South Africa, South Korea, and India, and two lines in the 1000-1200 kV range in Russia and Japan. A survey of technical literature revealed many publications on the planning and design aspects of the first generation of 700-800 kV transmission lines, but relatively few papers on the operation and maintenance aspects. Few publications were found for the second generation of 700-800 kV lines as well as for the 1000-1200 kV lines. As a result, a survey-type questionnaire was prepared in order to obtain comprehensive information on all aspects of the identified transmission lines. EPRI solicited the participation of the concerned utilities in the survey, and distributed the questionnaire to those who agreed to participate. A workshop was held in 2004 to discuss the questionnaire with experts from the participating utilities. Selected information collected

0-7803-9327-9/05/$20.00 ©2005 IEEE

through a literature survey, responses to the questionnaire were all used in preparing this paper. The complete survey and responses is contained within EPRI's 2004 Edition of the "AC Transmission Reference Book – 200kV and Above, 3rd Edition."

Even though many of the utilities that built lines at voltages greater than 700 kV had their own research programs, they also relied heavily on the research of others, especially the research conducted at the EPRI facility at Lenox, Massachusetts, which has been documented in three previously published reference books. This facility has been in operation since 1959 under many names: Project EHV, Project UHV, and the High Voltage Transmission Research Center. It has conducted pioneering research in all of the electrical phenomena associated with overhead high-voltage transmission lines, and has provided basic information not only for the design of lines above 700 kV, but also for the construction of research facilities such as test lines, test cages, contamination chambers, impulse generators, etc.

The paper begins with a brief review of the research and development efforts that were undertaken for the purpose of obtaining the data required for the design and construction of 700-800 kV and 1000-1200 kV transmission lines, followed by the main body of the chapter consisting of detailed case studies of nine 700-800 kV and two 1000-1200 kV lines. Each case study includes information on system planning, electrical design, mechanical and tower design, and operation and maintenance aspects. A summary is provided as part of this paper.

II. Research to Develop Transmission Systems Above 700 kV

A. Introduction

From 1934 to 1952, the United States had the only transmission systems in the world operating at voltages higher than 220 kV, which were the 287-kV lines from Hoover Dam in Nevada to Los Angeles in California. These lines, which used copper conductors, were later upgraded to 500 kV. For various reasons, no other systems were built in the United States or other countries to operate at higher voltages. However, shortly after World War II, the utility industry determined that there would be a need for higher-voltage transmission lines because of the great expansion in the use of electricity. This determination resulted in the construction of high-voltage test lines throughout the world, such as the Tidd 500-kV test project of American Gas & Electric and the Westinghouse Electric Corporation Company (Sporn and Monteith 1947). Other projects that were built to study higher voltages were the Chevilly 500-kV Experimental Station of Electricité de France (Cahen and Pelissier 1952); the Coldwater 600-kV test project of Ontario Hydro (Cassan and McMurtrie 1960); the Mannheim-Rheinau 400-kV Research Station in Germany (Bartenstein 1956); the 600-kV Shiobara Laboratory in Japan (Sawada 1965); and the 400-kV Leatherhead test line in England (Banks et al. 1968). Another important project of that era was the Leadville High-Altitude Extra-High-Voltage Test Project of the Public Service Company of Colorado and the Westinghouse Electric Corporation (Robertson and Dillard 1961). All these projects had three-phase test lines, with the exception of the Leatherhead and Leadville test lines, which had single-phase lines. These research projects provided the primary research that led to the construction of 345-kV, 400-kV, and 500-kV systems throughout the world. However, it should be noted that projects like Project EHV and Apple Grove, which were built to study voltages up to 775 kV, provided additional research for the 500-kV voltage class.

B. Research to Develop 800-kV Systems

In 1958, the General Electric Company determined that even higher voltages would be needed, which led to the construction of Project EHV in 1959 (Abetti 1960). This project provided research on corona and insulation for switching surge and power frequency voltages over the voltage range of 380-750 kV. It was located in the towns of Lenox and Lee, Berkshire County, Massachusetts. The location was chosen because it was only a few miles from the Pittsfield Transformer Plant of General Electric and from the General Electric High-Voltage Laboratory. The original Project EHV test line ran along the Housatonic River for a length of 4.3 miles (6.9 km) at elevations between 950 and 1080 ft (290 and 329 m) above sea level. The test line started operating as an open-ended line in 1960 at voltage levels between 460 and 500 kV. In 1961, terminal equipment was installed at the open end of the line, which completed the loop with a local 115-kV line. Project EHV was initially designed for two rated voltages, 460 and 650 kV. Insulation levels for the project were determined by conducting many impulse, switching surge, and 60-Hz tests on insulator strings, stacks of pedestal insulators, bushings, and various types of apparatus, under both wet and dry conditions.

Project EHV was operated under General Electric sponsorship from 1958 to 1964. The original project consisted of two EHV substations, a data acquisition and headquarters building, a 3000-kV outdoor impulse generator, and the test line. In 1964, General Electric proposed to the Edison Electric Institute that a two-year effort be undertaken to: (1) generalize the findings of the initial experience at the project, (2) bring to bear from this generalization all the analytical and computer models developed in parallel with the early project experience, and (3) continue experiments and tests at the project to fill in some important gaps in understanding that appeared necessary for effective generalized solutions (EEI 1968). This effort resulted in an EHV line design reference book (EEI 1968).

In 1960, the American Electric Power Service Corporation (AEP) entered into an agreement with the Westinghouse

Electric Corporation to build a test project that could operate over the range of 500-775 kV. This project, which consisted of three test lines, was energized in 1961, and was called the Apple Grove 750-kV Project (Shankle et al. 1965). The original project was instrumented to measure corona loss on all nine phases, with the conductors carrying simulated load current. It had three types of radio noise meters located at the electrical center of each test line.

Apple Grove originally was designed to operate for about five years. During that period the primary research was conducted on conductors operating at 775 kV, but one of the three test lines was reconductored, and the project was operated at 515 kV for one year starting in November 1962 (Taylor et al. 1965). During this same one-year period, switching surge tests were conducted on this 525-kV test line by reducing the phase-to-ground clearances artificially on one of the 775-kV suspension towers (Barnes et al. 1965). The results from this research were used in the design of the Virginia Electric & Power 500-kV line, which was the first line at this voltage level.

In 1969, which was about one year after AEP energized their first 765-kV line, the Apple Grove project was instrumented to measure audible noise. In 1974, ozone and television interference instrumentation were added. Extensive measurements of electric fields and induced currents and voltages into objects were conducted in the late 1960s and early 1970s.

Test projects to study voltages above 500 kV were built in other countries, such as the Experimental Station at Les Renardieres in France (Magnien et al. 1966) and the 700-kV single-phase test line that was built next to the Leatherhead High Voltage Laboratory in England (Banks et al. 1968). Test lines that operated in this voltage range were also built and operated in the USSR (Burgsdorf et al. 1960). In 1993, the Korea Electric Power Institute built the first double-circuit 765-kV test line near the Yellow Sea in South Korea (Dong-IL Lee et al. 1997). This project, which was called the "Gochang 765-kV Full Scale Test Line," was instrumented to measure all the phenomena associated with conductor corona.

As part of the Les Renardieres Research Project, a test cage to study corona phenomena was built. Such cages were found to be invaluable and were built in conjunction with some of the UHV research projects.

The majority of these test line projects were built to conduct research on conductor corona and ground-level electric fields. As was mentioned earlier, Project EHV had the capability of conducting lightning impulse and switching surge tests on tower configurations. In the development of 500-kV and 735/765-kV systems in the 1960s, utilities in North American conducted tests to determine the insulation needed for switching-surge overvoltages at Project EHV and/or at the high-voltage laboratories owned by manufacturers of high-voltage equipment. Most major manufacturers of high-voltage equipment—such as General Electric, Westinghouse, ASEA, Hitachi, etc.—had such high-voltage laboratories.

In 1979, Eskom entered into a collaborative program with both the Italian utility Ente Nazionale per L'Energia Elettrica (Enel) and the test lab Centro Elettrotecnico Sperimentale Italiano (CESI) of Italy. A high-altitude cage was built to study the effects of altitude on conductor corona phenomena, and in 1981/1982 two high-altitude 3300-kV UHV test laboratories (NETFA and CSIR) were built to study dielectric strengths of tower window shapes for 765-kV lines (Britten et al. 1987; Le Roux et al. 1987). Live-line working practices and insulation strengths were also studied. The laboratories were used, in addition, for the study of atmospheric correction factors for lightning and switching impulse breakdown, and also for the gap factors of various tower window shapes. The NETFA and CSIR labs were used mainly for switching and lightning impulse studies. Neither lab was equipped with a test line, and no laboratory studies of insulator pollution were conducted. However, some pollution severity measurements were done on a number of 88-kV test stations in the Johannesburg, KwaZulu Natal, and Cape areas. The equipment for these tests was acquired from Enel, and the work to some extent was guided by specialists in Enel and CESI. The 765-kV research at both laboratories was directed by Eskom specialists, but with guidance from Enel and CESI. The same applied to the research into conductor corona done at the Eskom Corona Cage.

Eskom never seriously considered the need for ac systems of 1000 kV and above. However, at the high operating altitudes of their present 765-kV system, the system is roughly equivalent to 1000 kV from a dielectric and corona point of view.

The research from these projects around the world resulted in the construction of thousands of miles of 735/765-kV lines in Québec, Canada and in the states served by AEP in the United States. The New York Power Authority (NYPA) and Commonwealth Associates built other lines operating at 765 kV in the U.S. In other countries, 765-kV lines were built in Brazil, Venezuela, South Africa, and South Korea. In the USSR, the lines that were built in this voltage range were classified as 787-kV lines.

C. Research to Develop Transmission Systems Above 1000 kV

Rapid load growth in the 1960s and the perceived prospects for continued load growth in the ensuing decades were the driving forces for research and development of ac power transmission lines at voltages above 1000 kV. Even as the first transmission lines at 500 and 750 kV were being built and operated in the 1960s, there was a heightened interest in developing the next higher transmission voltages in the so-called ultra-high-voltage (UHV) range of 1000 to 1500 kV (Anderson and Barthold 1968, Catenacci et al. 1968). In order to gather the vast amount of technical information necessary to design transmission lines above 1000 kV, research and test facilities were built in several countries in the 1970s. Information on the progress of research work carried out in six countries—Brazil, Canada, Italy, Japan, U.S., and USSR was presented in two excellent CIGRE Working Group (WG) reports (WG 31.04 1983; WG 38.04 1987).

The impetus for research on transmission lines above 1000 kV in Brazil was provided by the need for transmitting a block of power on the order of 20,000 MW from the Amazon Basin to the load centers at distances ranging from 1500 to 2300 km (De Franco and Morissy 1980). Research and test facilities required for carrying out studies at system voltages up to 1500 kV were built at the research institute Centro de Pesquisas de Energia Elétrica (CEPEL) in Adrianopolis, Brazil. In addition to a large indoor high-voltage laboratory for tests on equipment, the facilities at CEPEL include an outdoor area where full-scale or mockup transmission towers can be tested for air insulation clearances and an outdoor experimental line and test cages for corona studies.

In Canada, the need for transmission systems above 1000 kV was foreseen in the provinces of British Columbia and Québec to bring large blocks of power from remote hydroelectric projects to the load centers. The main research and test facilities for studies at system voltages above 1000 kV were located at the Institut de Recherche d'Hydro-Québec (IREQ), Hydro-Québec's research institute. The test facilities at IREQ (Hylten-Cavallius and Train 1974) comprised a large indoor high-voltage laboratory, with capabilities for air insulation studies on tower window mockups for system voltages up to 1500 kV, a large pollution chamber for studies on insulators, and an outdoor experimental line and test cages for corona studies. A test line was also built at Magdalen Islands to study vibration performance of conductor bundles and development of spacer dampers.

Phase-to-ground and phase-to-phase air insulation tests on line and substation configurations at IREQ provided a large amount of data necessary for determining air gap clearances for transmission lines and substations at system voltages of 1200 and 1500 kV. Corona studies were carried out in the test cages on six and eight conductor bundles, and the 6 x 46.53 mm conductor bundle was selected for 1200-kV lines (Trinh et al. 1974).

In Italy, opportunities were foreseen to install large power generation facilities at a few sites relatively far from the load centers (Cladé et al. 1978). It became apparent that, in order to take advantage of this opportunity, a new transmission voltage around 1000 kV would be required to overlay the existing 420-kV network. Studies for system voltages above 1000 kV were carried out in Italy at several research and test facilities. At the Suvereto 1000-kV Project, a 1-km-long test line was used for air insulation and corona studies. In addition, an outdoor test cage was also used for corona studies. A test line at Pradarena Pass was used for ice and wind loading studies in winter and vibration, subspan galloping, and spacer performance studies in summer. Further studies on air insulation and performance of polluted insulators were carried out at the CESI laboratories in Milan.

Extensive research studies carried at the different facilities in Italy generated a large amount of data for determining phase-to-ground and phase-to-phase air clearances, selecting ceramic and nonceramic insulator strings, and selecting conductor bundles for a 1050-kV prototype transmission line. The test data were also used in the development of vibration dampers, spacers, and nonconventional tower structures and foundations for 1050-kV transmission lines.

In Japan, the need for overcoming stability problems of the existing 500-kV network and obviating the problems of excessive short-circuit currents led to the consideration of transmission above 1000 kV to overlay the existing network. As a consequence, research and test facilities were built (Udo et al. 1980), comprising mainly a large fog chamber designed for testing polluted insulators at line-to-ground voltages up to 900 kV, a double-circuit experimental line, and a test cage for corona studies. In addition, a test line of the Tokyo Electric Power Company (TEPCO) was used for wind and ice studies on conductor bundles and the NGK high-voltage test facilities were used for corona and pollution studies. A significant amount of information was obtained on the withstand voltages of contaminated and snow-covered insulator strings.

In the United States, transmission voltages above 1000 kV were seriously considered by two utilities: AEP and Bonneville Power Administration (BPA). In both cases, the purpose of the new transmission systems was to transmit large amounts of power, improve system stability, and reduce environmental impact. Three separate research and test facilities were built to evaluate the technical feasibility of transmission lines above 1000 kV:

1. The AEP/ASEA test facility, located near South Bend, Indiana, had the capability of testing single-phase conductor bundles at voltages corresponding to transmission-system voltages up to, and even beyond, 1500 kV (Nagel and Vassell 1974; Pokorny and Flugum 1975). A single-phase experimental line and two test cages were used to evaluate the corona performance of large conductor bundles.
2. At BPA, a full-scale three–phase, 1200-kV prototype test line (Annestrand and Parks 1977) near Lyons, Oregon, was used to evaluate the long-term corona performance of an eight-conductor bundle. In addition, the facility at Carey High Voltage Laboratory was used for studies on air insulation, while conductor vibration and galloping studies were carried out at the Moro mechanical test line.
3. The GE/EPRI Project UHV comprised a three-phase experimental line, a test cage, and a pollution chamber. The facility had the capability of testing the corona performance of conductor bundles, withstand strength of air gaps, and the pollution performance of line and station

insulators. A detailed description of the test facilities is given in the second edition of the Red Book (EPRI 1982).

Data on the corona performance of several bundles, with up to 18 subconductors, were obtained at the AEP/ASEA test facility (Scherer et al. 1980). The results obtained at BPA included switching surge withstand strength of air gaps, pollution performance characteristics of ceramic and nonceramic insulator strings, and corona performance (Perry et al. 1979) of a seven- and an eight-conductor bundle. Eleven different conductor bundles, with subconductor diameters varying from 3.3 to 5.6 cm and the number of subconductors from 6 to 16, were tested at the GE/EPRI Project UHV at system voltages from 950 to 1450 kV to obtain a vast amount of data on the corona performance (EPRI 1982).

In the USSR, the need to strengthen the electrical links between integrated power systems, as well as the need for transmitting large quantities of power over long distances, spurred the research activities at transmission voltages in the range of 1150 to 1500 kV. A 1200-kV experimental line was constructed at the Bely Rast substation (Beliakov et al. 1976). Test data were obtained on the corona performance of conductor bundles and the strength of air insulation.

Although a large amount of research and test data was obtained from the different facilities around the world, the need to establish the technical feasibility of power transmission at voltages above 1000 kV, combined with economic and other considerations, persuaded the utilities concerned either to postpone indefinitely or abandon the plans for the construction of the transmission systems. A double-circuit 1000-kV transmission line was built in Japan, but has been operated only at 500 kV. The world's first 1200-kV transmission system (Burgsdorf et al. 1976) was built and operated for several years in the USSR. However, this system has been operated over the last few years at 500 kV.

III. Case Studies of Transmission Lines Above 700KV

The introduction of 735/765-kV systems began in the 1960s. There are three main reasons why such high-voltage systems were needed. The first reason was to transmit energy over long distances from remote generating sources to load centers. There are several examples that can be cited such as the Swedish 400-kV system, the Hydro-Quebec 735-kV system, and the 500-, 750- and 1150-kV systems in Russia.

Another important role of extra-high-voltage systems was to interconnect systems that had been previously isolated for the purpose of achieving economies in the use of generation sources. Examples can be found in Europe and on the Pacific Coast in the United States.

A third use of higher-voltage lines was to provide an overlay on an existing well-developed lower-voltage system. The purpose of such an overlay was to enable the bulk power transfer between generating plants and load centers, which permitted the integrated operation of the overall system in an economical and reliable manner. Such a system results in a complex network that is strongly interconnected with neighboring systems. Examples of such systems can be found all over the world, with the AEP 765-kV system as a prime example in the United States.

The summary of the line environments is presented in Table 1. These environments varied from flat to rolling to mountainous. The lines were built at altitudes close to sea level and as high as 1.8 km above sea level. For the most part they were built in pristine environments, but some line portions were built in moderate and heavily contaminated areas.

Table 1 Line Environments

Company/Country	Nominal Voltage (kV)	Terrain	Altitude Range km	Ground Resistivity (Ohms-m)	Contamination Level
Hydro-Québec 1	735	Rolling	<0.3	10–10000	Light
Hydro-Québec 2	735	Rolling	<0.3	10-10000	Light
AEP 1	765	Flat/Rolling/Mountainous	<0.1-1.0	10-10,000	Light
AEP 2	765	Flat/Rolling/Mountainous	<0.1-1.0	10-10,000	Light
AEP 3	765	Rolling/Mountainous	0.5-1.2	10-10,000	Light
NYPA	765	Flat/Rolling	<0.3	10,10000	Light
Eskom	765	Flat/Rolling	1 to 1.8	500-1500	Light
FURNAS	765	Flat	0 to 1.2	1000	Light
EDELCA	765	Plains/Hills	0.3 – 1.0	50 - 2000	Light-Heavy
KEPCO	765	Mountainous	.05 to 1.0	50 - 2000	Light-Heavy
POWERGRID	765	Plains/Hills	.2 -1.0	100 - 600	Light
Russia	750	Plains/Hills	0.1 – 0.5*	200 - 400	Light
Russia	1150	Plains/Hills	0.1 – 0.5*	200 –400	Light
Tokyo Electric	1000	Mountainous			Light-Heavy

* For Russian 750 kV, the insulation of both lines and substations equipment are designated for usage at altitudes up to 1 km, whereas for 1150 kV, the insulation is for lines up to 1 km and for substation equipment up to 0.5 km.

The number of sub-conductors used in the bundles of each line, along with the sub-conductor diameter, phase spacing, and minimum conductor heights, are presented in Table 2. All of the 765-kV lines built in the 1960s and 1970s have 4 subconductors. Russian 750-kV lines have 4 and mainly 5 subconductors. The Eskom lines being built at higher altitudes use 6 subconductors, as does the new line being built in the Appalachian Mountains in Virginia by AEP and the double-circuit low-reactance line built by KEPCO in Korea. Both of the lines built to operate above 1000 kV use 8 subconductors. The Russian 1150-kV line operated at that nominal voltage for a few years in the late 1980s and early 1990s, but lately has operated at 500 kV over more than 10 years. The TEPCO 1000-kV lines at this time are energized at 500 kV. Therefore, there are no lines operating anywhere in the world above 1000 kV at the present time.

The electrical environments of the lines operating above 700 kV are summarized in Table 3. The AN and RI values in

TABLE 2 LINE GEOMETRIES

Company/Country	Nominal Voltage (kV)	No. of Sub-conductors	Conductor Diameter (cm)	Phase Spacing (m)	Min. Conductor Heights* (m)
Hydro-Québec 1	735	4	3.50	15.3	15.3
Hydro-Québec 2	735	4	3.56	12.8	14.1
AEP 1	765	4	2.96	13.7	12.2
AEP 2	765	4	3.52	13.7	12.2/13.7
AEP 3	765	6	2.70	13.7	13.7
NYPA	765	4	3.52	15.2	15.5
Eskom	765	6	2.86	15.8	15.0
FURNAS	765	4	3.20	14.3	13
EDELCA 1 &2	765	4	3.33	15.0	14.7
EDELCA 3	765	4	3.33	13.2	13.7
KEPCO	765	6	3.042	See Note 1	19/28
POWERGRID	765	4	3.50	15.4	15
RUSSIA 1	750	5	2.24	17.5	12
RUSSIA 2	750	4	2.91	19	12
RUSSIA 3	1150	8	2.75	21.5-25	17.5
TEPCO	1000	8	3.42/3.84**	See Note 1	25/35

* Minimum heights in areas frequented by people including agricultural areas.
** Larger conductor used in populated areas; smaller conductor used in mountainous areas.
1. Double-circuit low reactance line

TABLE 3 LINE ELECTRICAL ENVIRONMENTS

Company/Country	Nominal Voltage (kV)	Width of right-of-way (m)	Mean Altitude (m)	Audible Noise (Rain) (dBA)	Radio Noise (Fair) @ 0.5 MHz (dBμV/m)	Max. Electric Field* (kV/m)	Electric Field Edge of Right-of-way (kV/m)
Hydro-Québec 1	735	91.5	<300	51.2	43.0	8.7	1.5
Hydro-Québec 2	735	80.0	<300	54.7	46.4	9.3	1.7
AEP 1	765	60.1	<300	59.2	55.4	12.4	4.0
AEP 1	765	60.1	600	61.2	57.4	12.4	4.0
AEP 2	765	60.1	600	57.5	52.8	10.5	4.1
AEP 3	765	91.4	800	54.5	45.8	11.2	4.4
NYPA 1	765	106.7	<300	50.5	42.8	9.2	1.6
Eskom	765	80.0	1500	53	62	10	2.4
FURNAS 1 & 2	765	175**	800	58	42	5/10/15	< 4.2
FURNAS 3	765	94.5	800	58	42	5/10/15	< 4.2
EDELCA 1 & 2	765	120.0	<300	52.2	38.4	9.5	0.7
EDELCA 3	765	90.0	<300	55.0	44.2	10.2	1.3
KEPCO 1	765	37.0	<300	50.0	44.0	3.5/7.0	3.5
POWERGRID	765	85/64	<300	54.3	43.5	10	2.0
RUSSIA 1	750	116.0	<300	50.1	39.7	5/15/20†	1.0
RUSSIA 2	750	116.0	<300	52.3	42.6	5/15/20†	
RUSSIA 3	1150	245.6	<300	51.8	29.4	5/15/20†	
TEPCO	1000	39	<300	46.8	34.9	3.5/7.0	3.5

* Smallest values are for areas frequented by people.
** The transmission lines 1 & 2 are parallel in the same right-of-way.
† 5 kV/m in populated areas. 15 kV/m in unpopulated areas reserved for agriculture; 20 kV/m in areas not accessible by agricultural machinery. No limit for unpopulated in inaccessible areas such as steep slopes, mountains, etc.

this table were obtained by using the BPA empirical models. The authors tried to create this table using the design values provided by each electric utility, but this attempt was abandoned for the following reasons: (1) AN was not an issue when the original Hydro-Québec and AEP lines were built; (2) AN levels were calculated by the individual utilities using various empirical formulas under various weather conditions that were available at the time the lines were being designed; and (3) the RI levels were calculated using different formulas for different weather conditions, different frequencies, and different standards using formulas that were available at the time the lines were being designed. The electric field values were provided by the corresponding utility representatives.

For the KEPCO and TEPCO lines, the values in Table 3 were calculated for populated areas. In the mountainous areas of Korea and Japan with no population, the lines are closer to the ground and the electric fields are higher.

The levels in Table 3 were calculated at the edge of the right-of-way except for Russia. Russia does not have rights-of-way. They have what they call "Security Zones" for their high-voltage lines. The security zone is defined by a boundary on both sides, and construction is not allowed within the zone. For the 750-kV lines, it is 40 m from the outside phase, and for the 1150-kV line it is 100 m. The zone width then is 80 m + 2D for 750-kV lines and 200 m + 2D for the 1150-kV lines, where D is the phase spacing of each line. This creates a very wide "right-of-way" for the Russian lines as compared to the lines in the rest of the world.

Based upon the responses to the questionnaire, it appears that lines built to produce L50 rain AN levels less than 55 dBA have experienced few or no complaints, whereas lines that produced AN levels above 55 dBA have had either moderate or scattered complaints. The number of RI and TVI complaints has been quite small, and they have been easily resolved. As would be expected, some of the lines have had complaints about spark-discharges from the electric field, but most of those have been easily resolved through grounding and education.

The insulation characteristics used for all the lines are summarized in Table 4. The lines utilized either glass or porcelain insulators of various ratings. However, the new AEP line to be built in the Appalachian Mountains in Virginia with a 6-conductor bundle will use nonceramic insulators (NCI's). This will be the first line that will be fully insulated with NCIs at voltages above 700 kV. Based upon the responses to the questionnaire, none of these lines has had outages due to switching surges. Russia and Venezuela have had outages due to insulator contamination. For the most part, all of the lines were built in pristine environment, which explains the lack of outages due to contamination. However, there have

TABLE 4 INSULATION CHARACTERISTICS OF SUSPENSION TOWERS

Company/Country	Nominal Voltage	Minimum Strike Distance (m)	Insulator Type	No. in string	M&E Rating (kN)	ESDD (mg/cm2)	Creepage (mm/kV)
Hydro-Québec 1	735	4.1	Porcelain	33	110/160	0.03	14
Hydro-Québec 2	735	4.1	Porcelain & Glass	33	110/160	0.03	14
AEP 1	765	4.26	Porcelain	30/32	25/36/50*		15
AEP 2	765	4.26	Porcelain	30/32	25/36/50*		
AEP 3	765	4.26	Polymer	NA	NA		
NYPA	765		Porcelain	35	30		19.8
Eskom 1	765	5.5	Glass	33	300		
Eskom 2	765	5.5	Glass	30			
FURNAS 1	765	5.0/7.0	Glass	30	120		12.55
FURNAS 2 & 3	765	5.0/6.5	Glass	30	160		12.55
EDELCA 1 & 2	765	5.5 no wind 4.0 wind	Porcelain & Glass	37	160/210	0.05 0.24	17.9 26.1
EDELCA 3	765	5.07	Porcelain & Glass	37	160/210	0.05 0.24	17.9 26.1
KEPCO	765	4.9	Porcelain	37/36	300/400	0.03	16.9
POWERGRID	765	5.1 – 5.6 4.4 wind	Porcelain & Glass	40/35	120/210	0.03	16.9
Russia	750	4.1 – 4.5	Glass	41	Mainly** 120/160		15
Russia	1150	.5	Glass	63/67	Mainly** 210/400		15
Tokyo Electric	1000		Porcelain	40			

Units are kilopounds (kips).
** Specifications permit the use of insulators from 120 to 400 kN, depending on the load on the I or V strings in either single or double circuit.

been outages due to lightning, with the frequency of outages corresponding well with the expected outage rate. Some utilities have had outages due to wind and ice causing towers to collapse.

Towers and foundations for each line and the mechanical/structural design criteria used are summarized in Table 5. All of the single-circuit lines are horizontally configured, although the POWERGRID in India is building new lines with delta configuration. Most of the towers are self-supporting, although Hydro-Québec, Eskom, AEP, and FURNAS have some lines with guyed-V structures. Russia uses almost exclusively guyed support structures. Most of the foundations are the grillage type, but many are the caisson type.

Overhead ground wire parameters and grounding systems used for all of the lines, along with the IKL, lightning flash density, and shielding angle are given in Table 6. As would be expected, the shield angle is much smaller for lines that are in environments with high lightning incidences. Most grounding systems use counterpoise. In Russia, the self-grounding via foundations usually provides grounding resistance close to 15 ohms.

With regard to inspection, all of the utilities have similar programs, which combine ground patrols and tower climbing. Most utilities are using helicopters for line inspection.

A variety of techniques are used to maintain these lines. AEP, for example, today makes every effort to conduct maintenance on de-energized lines even though they were a pioneer in the development of bare-handed techniques. Conducting maintenance on de-energized lines has become the preferred method of most utilities. However, live line work is also being conducted using helicopters, especially for spacer and spacer damper replacements.

Both PLC and microwave have been used by the utilities for communication, with some relying totally on PLC and others totally on microwave. However, OPGW is being incorporated by several utilities.

Lightning detection systems that are correlated with the GPS coordinates of their transmission structures are being used by most of the utilities.

TABLE 5 TOWER TYPES, FOUNDATIONS AND DESIGN LOADINGS

Company/ Country	Nominal Voltage (kV)	Tower types	Material	Foundation	Design Wind/Ice Loadings
Hydro-Québec 1	735	SS*	Gal. Steel	Grillage	385 Pa/ 12.7 mm
Hydro-Québec 2	735	SS, Guyed V & Chainette	Gal. Steel	Grillage	300 Pa/ 20 mm (1) 230 Pa/ 10 mm (2)
AEP 1	765	SS & Guyed-V	Gal. Steel & Alum	Grillage/ Caisson	300 Pa/ 25.4 mm
AEP 2	765	SS & Guyed-V	Gal. Steel & Alum	Grillage/ Caisson	300 Pa/ 25.4 mm
AEP 3	765	SS & Guyed-V	Gal. Steel	Grillage	300 Pa/ 25.4 mm
NYPA	765	SS	Gal. Steel	Grillage	190 Pa/ 1.25 mm (8)
Eskom	765	SS & Guyed-V	Gal. Steel Alum.	Caisson	32/45 m/s (3)
FURNAS	765	SS & Guyed-V	Gal. Steel	Grillage	150 km/h (4)
EDELCA	765	SS	Gal. Steel	Spread Footing & Piled	125 km/h (5)
KEPCO	765	SS	Tubular Steel	Caisson	(6)
POWERGRID	765	SS	Steel		47 m/s (7)
Russia	750	Guyed V	Steel	Isolated Footing & Piled	540-640 Pa/ 15-20 mm
Russia	1150	Guyed V	Steel	Caisson	700-800 Pa/ 10-15 mm
TEPCO	1000	SS	Tubular Steel	Caisson	

* SS - self-supporting; (1) – Southern zone; (2) – Northern zone; (3) – 32 m/s wind on conductors and 45 m/s wind (1.4 gust factor) on the tower; (4) – maximum 30-s duration wind speed at 30 m height and 50-year return period; (5) – maximum 5-s duration wind speed at 10 m height and 200-year return period; (6) – no single value; (7) – maximum wind speed with 150-year return period and also narrow-front wind of 240 km/h; (8) – correspond to NESC Heavy.

TABLE 6 OVERHEAD GROUND WIRES AND LIGHTNING PROTECTION

Company/ Country	Nominal Voltage (kV)	Overhead Ground Wire Diameter (cm)	Overhead Ground Wire Spacing (m)	IKL	Lightning Flash Density (Ls-g/km2/yr)	Shielding Angle (Degrees)	Grounding System	Tower Footing Resistance (Ohms)
Hydro-Québec 1	735	1.27	21.5	20/5	1-2	20	Continuous counterpoise	< 25
Hydro-Québec 2	735	1.27	19.5	20/5	1-2	20	Continuous counterpoise	< 25
AEP 1	765	0.98	22		2-4/km2/yr	15	Foundation	<10 Target
AEP 2	765	0.98	22		2-4/km2/yr	15	Foundation	<10 Target
AEP 3	765	0.98	22		2-4/km2/yr	15	Foundation	<10 Target
NYPA	765	1.159	22.8	30		20	Counterpoise	< 30
Eskom	765		28.2		6-9	2.4		10
FURNAS 1	765	0.914/1.219	27.2	100			Counterpoise	15
FURNAS 2	765	1.219/1.542	27.2	100			Counterpoise	15
FURNAS 3	765	0.914/1.219/ OPGW	27.2	100			Counterpoise	15
EDELCA 1&2	765	0.978	22.5	50/80	6-10	20	Counterpoise	< 20
EDELCA 3	765	0.978	21.3	50/80	6-10	20/0	Counterpoise	< 20
KEPCO	765	1.9	31.0	20		-8.0	Counterpoise	< 15
POWERGRID	765	1.098	22.4	50/60	6-8		Pipe Counter-poise	10
Russia	750	1.54**	15-27		(20-50)*	20/22	Foundation	< 15
Russia	1150	Bundle of two 1.54	35		(20-50)*	20/22	Foundation	< 15
Tokyo Electric	1000		38			-12	Counterpoise	< 15

* Thunderstorm hours/year.

REFERENCES

[1] Abetti, P.A. 1960. "Project E.H.V." CIGRE Paper 406.

[2] Anderson, J. G. and L. O. Barthold. 1968. "Design Challenges of Transmission Lines Above 765 kV." IEEE-EHV Transmission Conference (Publication 68 C 57 – PWR). September 30th to October 2nd. Montreal, Quebec, Canada.

[3] Annestrand, S. A. and G. A. Parks. 1977. "Bonneville Power Administration Prototype 1100/1200 kV Transmission Line Project." IEEE Transactions on Power Apparatus and Systems. Vol. PAS- 96. No. 2. pp. 357-366. March/April.

[4] Banks, M. J. J., R. Keitley, and G. C. Stringfellow. 1968. "Radio Noise and Corona Loss Studies at 275/400 and 750 kV on Test and Operational Power Lines." IEE Conference on Progress in Overhead Lines and Cables for 220 kV and Above. p. 306.

[5] Barnes, H. C., A. J. McElroy, D. F. Shankle, and H. M. Smith. 1965. "The Apple Grove 750-kV Project—500-kV Switching Surge and Line Flashover Tests." IEEE PAS-84. pp. 550-560.

[6] Bartenstein, R. 1956. "Measurements of Corona Losses and Interference Levels at the 400 kV Research Station at Mannheim-Rheinau (Germany) with Special Reference to Bundle Conductors." CIGRE Paper 402.

[7] Bartenstein, R., F. Hirsch, and E. Schafer. 1966. "Corona Measurements on a Four-Conductor Bundle for 700 kV Three-Phase Overhead Lines." CIGRE Paper 426.

[8] Beliakov, N. N. et al. 1976. "1150 kV Experimental Installation at Bely Rast Substation." CIGRÉ Report 23-03.

[9] Britten, A. C., E. G. Clarke, and H. E. Konkel. 1987. "Radio Interference, Corona Losses, Audible Noise and Power Frequency Electric Fields as Factors in the Design of ESCOM's 765 kV Lines." Open Conference on EHV Transmission Systems. Eskom Megawatt Park Auditorium. 23 November.

[10] Burgsdorf, V. V., L. V. Egorova, N. P. Emeljanov, and N. N. Tihodeev. 1960. "Corona Investigation on Extra-High Voltage Overhead Lines." CIGRE Paper 413.

[11] Burgsdorf, V. V. et al. 1976. "Design of the EHV (1150 kV) AC Transmission Line." CIGRÉ Report 31-03.

[12] Cahen, F. and R. Pelissier. 1952. "Experience Gained at the 500 kV Test Station of Chevilly during the Period 1950 and 1951." CIGRE Paper 406.

[13] Cassan, J. G. and N. J. McMurtrie. 1960. "The Coldwater 600 kV Experimental Line." CIGRE Paper 408.

[14] Catenacci, G., G. Carrara, G. Furioli, and L. Dellera. 1968. "1500 kV A.C. Lines: A First Look on the Main Electrical Design Problems." IEEE-EHV Transmission Conference (Publication 68 C 57 – PWR). September 30th to October 2nd. Montreal, Quebec, Canada.

[15] CIGRE. 1983. WG 31.04 Report. "Electric Power Transmission at Voltages of 1000 kV and Above: Plans for Future AC and DC Transmission, Data on Technical and Economic Feasibility and on General Design, Information on Testing Facilities and the Research in Progress." Electra. No. 91. pp. 83-133.

[16] CIGRE. 1989. WG 38.04 Report. "Electric Power Transmission at Voltages of 1000 kV AC or ±600 kV DC and Above: Network Problems and Solutions Peculiar to UHV AC Transmission." Electra. No. 122. pp. 41- 75.

[17] Cladé, J., P. Maréchal, G. Manzoni, L. Paris, and M. Valtorta. 1978. "Factors on Which to Base Comparisons in Choosing the Higher Voltage Level for a Transmission Network." CIGRÉ Report 31-5.

[18] Coney, R.G. 1987. "The Protection of ESKOM's Alpha and Beta 400/765 kV Transmission Lines." Open Conference on EHV Transmission Systems. Eskom Megawatt Park Auditorium. 23 November.

[19] Cretchley, D. H., W. L. Eaterhuizen, and G. M. Ferrero. 1987. "Design and Construction of ESCOM's First 765 kV Transmission Lines." Open Conference on EHV Transmission Systems. Eskom Megawatt Park Auditorium. 23 November.

[20] De Franco, N. and C. A. S. Morissy. 1980. "An Account of Long-Term Transmission System Development in Brazil." CIGRÉ Report 31-13.

[21] EEI. 1968. EHV Transmission Line Reference Book. Edison Electric Institute. New York, New York.

[22] EPRI. 1982. *Transmission Line Reference Book: 345 kV and Above.* Second Edition, Revised.

[23] Garrity, T., J. C. Haahr, L. Knudsen, and M. C. Raezer. 1972. "Experience with the AEP 765-kV System – Part V – System Performance." 1972 IEEE/PES Winter Power Meeting. January.

[24] Haas, R. J., J. D. Heiermann, and R.W. Schooley. 1972. "Experience with the AEP 765-kV System – Part IV – Overvoltage and Staged Fault Tests: Analysis." 1972 IEEE/PES Winter Power Meeting. January.

[25] Hauspurg, A., G. S. Vassell, G. I. Stillman, J. H. Charkow, and J. C. Haahr. 1969. "Overvoltages on the AEP 765-kV System." IEEE PAS-88. pp. 1329-1342. September.

[26] Hauspurg, A., V. Caleca, and R. H. Schlomann. 1969. "765-kV Transmission Line Insulation: Testing Program." IEEE PAS-88. pp. 1355-1365. September.

[27] Hylten-Cavallius, N. and D. Train. 1974. "The IREQ Ultra High Voltage Laboratory and Test Facilities." IEEE Transactions on Power Apparatus and Systems. Vol. PAS-93. No.

[28] 1. pp. 255-263. January/February.

[29] KEPCO. 2003. 765-kV Transmission and Substation. Korea Electric Power Corporation—Power System Construction Office. Seoul, Korea.

[30] Keri, A. J. F., A. Nourai, and J. M. Schneider. 1984. "The Open Loop Scheme: An Effective Method of Ground Wire Loss Reduction." IEEE PAS-103. pp 3615-3624. December.

[31] Kolcio, N., B. J. Ware, R. L. Zagier, V. L. Chartier, and

[32] F.M. Dietrich. 1974. "The Apple Grove 750 kV Project: Statistical Analysis of Audible Noise Performance of Conductors at 775 kV." IEEE PAS-93. pp. 831-840. May/June.

[33] Krylov, S. V. 2004. "Design, Mechanical Aspects and Other Subjects of Compact EHV Overhead Line Technology." Presented at Midwest ISO-Expanding Seminar on High Surge Impedance Loading Transmission Line Design and Magnetically Controlled Reactors. St. Paul, Minnesota. September 16.

[34] Le Roux, B. C., A. C. Britten, K. J. Sadurski, and A. W. Chilton. 1987. "A Review of EHV Air-Breakdown Studies in South Africa." Open Conference on EHV Transmission Systems. Eskom Megawatt Park Auditorium. 23 November.

[35] Lee, Dong-I L., J. B. Kim, and K. H. Yang. 1997. "Audible Noise Performance of 6-Rail Conductors on a 765-kV Double Circuit Test Line." IEEE PWRD-12. pp. 13431351. July.

[36] Magnien, M., J. Clade, and C. Gary. 1966. "The 'Electricite de France' Test Station for Corona Studies on Future

[37] E.H.V. Lines." CIGRE Paper 427.

[38] Nagel, T. J. and G. S. Vassell. 1974. "Development of the American Electric Power System Transmission Network: From 345 kV to 765 kV to UHV." CIGRÉ Report 32-13.

[39] Norman, H. B. 1988. "Why a 765 kV Transmission System?" Elektron. pp. 5-14. January.

[40] Nourse, G. R. 1969. "Development and Trial Installation of an Aluminum Tubing Audible Noise Suppressor for 765 kV Lines." IEEE PAS-97. p. 1009. July/August.

[41] Peixoto, C. A. O. 1980. "Itaipu 6300 MW HVDC Transmission System—Feasibility and Planning Aspects." Symposium on Incorporating HVDC Power Transmission into System Planning. Sponsored by U.S. Department of Energy. Phoenix, Arizona.

[42] Perry, D. E., V. L. Chartier, and G. L. Reiner. 1979. "BPA 1100 kV Transmission Development—Corona and Electric Field Studies." IEEE Transactions on Power Apparatus and Systems. Vol. PAS- 98. pp. 1728-1738. September/October.

[43] Pokorny, W. C. and R. W. Flugum. 1975. "UHV Tower Insulation Parameters Defined by Full-Scale Testing." IEEE Transactions on Power Apparatus and Systems. Vol. PAS-94. No. 2. pp. 518-529. March/April.

[44] Power System Planning Division of Tokyo Electric Power Company. 1985. "Plan and General Design for 1000-kV Transmission in Japan." Report Presented at the Japanese National Panel of CIGRE WG38-04. June.

[45] Robertson, L. M. and J. K. Dillard. 1961. "Leadville High Altitude EHV Test Project, Part I – Report on 4 Years of Testing" AIEE Transactions on Power Apparatus and Systems, pp. 715-25, December.

[46] Samuelson, A. J., R. L. Retallack, and R. A. Kravitz. 1969. "AEP 765-kV Line Design." IEEE PAS-88, pp. 1366-1371. September.

[47] Sawada, Y. 1965. "Corona Noise Characteristics of Four-Conductor Power Transmission Lines." J. IEE (Japan). Vol.

[48] 85. pp. 62-72. January.

[49] Scherer, Jr., H. N. and G. S. Vassell. 1972. "Experience with the AEP 765-kV System – Part I: Overview." 1972 IEEE/PES Winter Power Meeting. January.

[50] Scherer, Jr., H. N., S. H. Horowitz, and R. A. Byron. 1972. "Experience with the AEP 765-kV System – Part III- Construction and Equipment Performance Considerations." 1972 IEEE/PES Winter Power Meeting. January.

[51] Scherer, H. N. et al. 1980. "The AEP-ASEA UHV Project. Results to 1979." CIGRÉ Report 31-04.

[52] Shankle, D. F., S. B. Griscom, E. R. Taylor, Jr., and R. H. Schlomann. 1965. "The Apple Grove 750-kV Project – Equipment Design and Instrumentation." IEEE PAS-84. pp. 541-550. July.

[53] Sporn, P. and A. C. Monteith. 1947. "Transmission of Electric Power at Extra High Voltages." AIEE Transactions on Power Apparatus and Systems. Vol. 66. pp. 1571-82.

[54] Tamazov, A. I. 2004. "Corona on Conductors of AC Overhead Transmission Lines." Sputnik Publishing House. Moscow.

[55] Taylor, E. R., W. E. Pakala, and N. Kolcio. 1965. "The Apple Grove 750-kV Project – 515-kV Radio Influence and Corona Loss Investigations." IEEE PAS-84. pp. 561573. July.

[56] Tokyo Electric Power Company. 1994. "1000 kV Transmission Lines." A Special Publication of the Tokyo Electric Power Company.

[57] Trinh, N. G., P. S. Maruvada, and B. Poirier. 1974. "A Comparative Study of Corona Performance of Conductor Bundles for 1200 kV Transmission Lines." IEEE Transactions on Power Apparatus and Systems. Vol. PAS-93. No.3. pp. 940-949. May/June.

[58] Udo, T., M. Yasui, and T. Fujimura. 1980. "An Outline of Testing Facilities for Research of UHV Transmission Lines and Some Test Results in Japan." CIGRÉ Report 31-02.

[59] Vassell, G. S. and R. M. Maliszewski. 1969. "AEP 765-kV System: System Planning Considerations." IEEE PAS-88. pp. 1320-1328.

[60] Vassell, G. S., R. M. Maliszewski, and N. B. Johnsen. 1972. "Experience with the AEP 765-kV System–Part II: System Performance." 1972 IEEE/PES Winter Power Meeting. January.

BIOGRAPHIES

Raymond Lings is the Area Manager for Transmission and Substations within the Science and Technology Development Division of EPRI. In his present duties, Lings is responsible for the management and execution of EPRI's research in overhead and underground transmission, substations, increased transmission capacity, EMC (electromagnetic compatibility), energy storage for T & D applications, and applications of superconductivity. Lings joined EPRI in 1998 as a project manager in substations. Prior to joining EPRI, he was the Research Operations Manager at Eskom, South Africa, where he worked for 11 years, starting as an Engineer-in-Training and rising to Manager of Electrical Research and then to Research Operations Manager covering research in distribution, transmission, and generation. As Manager of Electrical Research, he managed Eskom's extensive electrical laboratories. Lings is a senior member of the IEEE and is a registered professional engineer in South Africa. He is the author or co-author of more than 15 publications in the field of transmission and distribution, with the majority of his publications covering electronic domestic metering. As EPRI project manager for this edition of the Reference Book, Lings led the editorial committee, and had overall management responsibility for the new edition. He has also represented South Africa and now the United States on an IEC Working Group on the reliability of metering. Lings holds a number of degrees including a Masters Degree in Electrical Engineering (MSc) and a Masters of Business Administration (MBA).

Vernon L. Chartier has conducted pioneering research on the corona and field effects of several lines operating above 700 kV, which made him uniquely qualified along with Dr. Maruvada to write this chapter. From 1964 to 1975, he managed the Apple Grove 750-kV Project located along the Ohio River in West Virginia for the Westinghouse Electric Corporation. This facility was a joint project of the American Electric Power Service Corporation (AEP) and Westinghouse, which led to the extensive 765-kV network built by AEP, starting in the late 1960s. In 1968, while at Westinghouse, he conducted extensive EMI measurements for the United States Air Force from 30 Hz to 10,000 MHz on one of the Hydro-Quebec 735-kV lines. Starting in 1974, he was a consultant and expert witness for three electric utilities in New York State on proposed 765-kV lines that resulted in what is commonly known at the "Common Record Hearings on Health and Safety of Extra-High Voltage Transmission Lines." In 1975, he joined the Division of Laboratories of the Bonneville Power Administration (BPA), where he played a major role in BPA's research on a prototype 1200-kV line built near Lyons, Oregon. While at BPA, he also managed several high-voltage research projects to gain a better understanding of the electric environment on both high-voltage ac and dc lines. Three of the more significant projects were: (1) EMI and AN measurements on a double-circuit 500-kV line at an altitude of 1935 m above sea level near Basin, Montana; (2) EMI, AN, and ion-enhanced electric field measurements on the upgraded ±500-kV HVDC line near Grizzly Mountain in Oregon; and (3) EMI and AN measurements on a compact 230-kV line of Puget Sound Power and Light near Sedro-Wooley, Washington. He has also assisted the Korea Electric Power Research Institute (KEPRI) in the siting and associated research conducted at the Gochang 765-kV Full-Scale Double Circuit Test Line located on the western coast of Gochang-Gun, Jeon-buk Province in South Korea. His research has been documented in more than 50 technical papers. From 1995 to the present, he has been an independent consultant on Power System Electromagnetic Compatibility (EMC). He has played a leading role in the corona and fields work of IEEE, CIGRE, and CISPR. For his contributions he was elected a Fellow of IEEE in 1980; received the IEEE Herman Halperin Transmission and Distribution Award in 1995, and the IEEE Third Millennium Medal in 2000; and was inducted into the National Academy of Engineers in 2004.

Dr. P. Sarma Maruvada has been involved in theoretical and experimental research studies of the corona performance of high-voltage ac and dc transmission lines for more than 35 years. He has made important contributions to the calculation of conductor surface electric fields; analysis of corona onset phenomena, space charge fields, and corona losses of dc transmission lines; analysis and measurement of radio noise and audible noise; and development of design criteria for radio noise and audible noise of ac and dc transmission lines as well as for electric fields and ion currents in the vicinity of dc lines. He contributed to the research and development of the 1200-kV ac transmission option that was considered by Hydro-Québec in 1974 for the James Bay Project. He also assisted in the development of research facilities at the Central Power Research Institute (CPRI), Hyderabad, India, for carrying out the electrical studies at transmission voltages up to 1200 kV ac and ± 1000 kV dc.

Dr. Maruvada's research and analysis of corona are presented in his landmark book Corona Performance of High-Voltage Transmission Lines. He served on the Executive Committee of the IEEE/PES Transmission and Distribution Conference and Exposition and as Chairman of CIGRE Study Committee 36 on Power System Electromagnetic Compatibility. He is an Honorary Member of CIGRE, has been elected Fellow of IEEE and received the IEEE Herman Halperin Electric Transmission and Distribution Award.