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ANL/EVS/TM/08-4

The Design, Construction, and Operation of Long-Distance High-Voltage Electricity Transmission Technologies

Environmental Science Division

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The Design, Construction, and Operation of Long-Distance High-Voltage Electricity Transmission Technologies

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November 2007

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The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) used in this document. Acronyms and abbreviations used only in tables and figures are defined in the respective tables and figures.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

AC	alternating current
ACCR	aluminum conductor composite reinforced
ACSR	aluminum conductor steel reinforced
BSCCO	bismuth strontium calcium copper oxide
BLM	Bureau of Land Management
BMP	best management practice
BPA	Bonneville Power Authority
BZO	barium zirconate
CD	cold dielectric
DC	direct current
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ERCOT	Electric Reliability Council of Texas
EIA	Energy Information Administration
EIS	Environmental Impact Statement
ELF	extremely low frequency
EMF	electromagnetic field
ESRI	Environmental Systems Research Institute, Inc.
GIS	geographical information system
HTS	high-temperature superconductor
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IEEE	Institute of Electrical and Electronic Engineers, Inc.
IGBT	insulated-gate bipolar transistor
LN2	liquid nitrogen
LTS	low-temperature superconductor
LTT	light-triggered thyristor

NCEP	National Commission on Energy Policy
NHPA	National Historic Preservation Act
OPIT	oxide powder in tube
OSHA	Occupational Safety and Health Administration
RMS	root mean square
ROW(s)	right(s)-of-way
SDGE	San Diego Gas & Electric
SEC	sealing end compound
TEP	Tucson Electric Power
USFS	U.S. Forest Service
VSC	voltage sourced converter
WD	warm dielectric
YBCO	yttrium barium copper oxides

UNITS OF MEASURE

A	ampere(s)
cm	centimeter
°C	degree(s) Centigrade
dB	decibel(s)
Hz	hertz
K	Kelvin
kA	kiloampere(s)
km	kilometer(s)
kV	kilovolt(s)
lb	pound(s)
m^2	square meter(s)
µT	micro Tesla
m	meter(s)
MPa	megapascal(s)
MVA	megavolt ampere(s)
MVAR	megavolt-ampere(s) reactive
MW	megawatt(s)
T	Tesla
V	volt(s)
W	watt(s)

1 ELECTRICITY TRANSMISSION SYSTEM OVERVIEW

1.1 INTRODUCTION

Early on in the development of electric power, its proponents and developers recognized the importance of economies of scale in power generation. If power could be distributed to a broader customer base, larger, centralized generation facilities could be built providing power at much lower costs. In turn, these lower costs would attract more customers, making even larger scale production possible. However, several factors limit the practical scale of central generation. Most obviously, the practical size of boilers, turbines, and other generating plant equipment is limited by the ability to manufacture and transport this equipment to a plant site. Over the last century, commercial power equipment has evolved such that practical generating station capacities have increased from 5 megawatts (MW)[1] to several thousand megawatts. In the absence of other constraints, central plant size could continue to increase, at least in a modular fashion, by adding more and more units of similar design at a given site. There are other constraints, though, so that the practical size of central generating facilities may actually decline in the future. These constraints include fuel and resource supply at a given site, limits imposed by the natural environment for dissipating waste heat, transport and disposal of waste products, community environmental standards, reliability and security concerns, and the economics of power transmission.

As central power station size increased, the plant operators faced myriad challenges in distributing power to customers. Photographs of commercial urban areas in the early years of the twentieth century often reveal a labyrinth of overhead wires from competing suppliers of power (and also of communications). This highly inefficient example of competitive markets was tamed by a system of regulation granting a limited monopoly to selected firms in exchange for providing reliable power service to a community. The development of the regulated industry structure further encouraged centralization of power production and the need for larger distribution networks. By 1910, Samuel Insull had begun rural electrification, so long-distance distribution to rural and other remote customers was needed. In some cases, these developing distribution systems were linked, connecting several generating stations and improving the reliability of power supply.

Among the limiting factors to centralization is the increasing cost of distributing power. This cost has both significant capital-investment and operating-cost components. The operating cost is principally due to power lost through electrical resistance. As the line length increases, so does the resistance loss. Electrical resistance converts electric power into thermal energy, which is lost to the atmosphere. At least through the 1980s, utility engineers in the Midwest estimated the power lost through transmission and distribution at 7% of the power leaving the generating station (the bus bar power output). This common experience suggests that 7% line loss was the optimum economic trade-off against the economies of scale inherent in the centralization of power production.

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[1] In 1902, a 5-MW turbine was installed at the Fisk St. Station in Chicago.

To clearly describe power transmission facilities, it is necessary to draw a distinction between transmission and distribution, both of which refer to the transport of electricity. Distribution refers to supplying power to retail customers. Distribution lines normally run from substations through a distribution line network. The key distinction between distribution and transmission arises from the issue of resistive power loss and the fact that the power loss can be reduced by increasing the operating voltage of a line. The final distribution of electrical power to retail customers occurs over relatively short distances, while much longer distances are typically associated with electrical transmission between power plants or between power generators and the sometimes remote communities that they serve. Accordingly, one would expect to find high operating voltages to be a characteristic of transmission lines. Actually, transmission line voltage is normally 115,000 volts (115 kilovolts [kV]) or higher (EIA 2002). In contrast, primary distribution lines generally reach distances of no more than a few miles, although in rural areas they may extend more than 50 miles (Hayes 2005). These lines generally range from 2.4 to 25 kV with occasional installations up to 46 kV (Hayes 2005). In some cases, customers are served directly at these high voltages, but most customers receive power by means of secondary distribution lines that branch off the primary lines at voltages of 120 V or 240 V. These low-voltage lines generally traverse only a few hundred yards.

This report focuses on transmission lines, which operate at voltages of 115 kV and higher. Currently, the highest voltage lines comprising the North American power grid are at 765 kV. The grid is the network of transmission lines that interconnect most large power plants on the North American continent. One transmission line at this high voltage was built near Chicago as part of the interconnection for three large nuclear power plants southwest of the city. Lines at this voltage also serve markets in New York and New England, also very high demand regions. The large power transfers along the West Coast are generally at 230 or 500 kV. Just as there are practical limits to centralization of power production, there are practical limits to increasing line voltage. As voltage increases, the height of the supporting towers, the size of the insulators, the distance between conductors on a tower, and even the width of the right-of-way (ROW) required increase. These design features safely isolate the electric power, which has an increasing tendency to arc to ground as the voltage (or electrical potential) increases. In addition, very high voltages (345 kV and above) are subject to corona losses. These losses are a result of ionization of the atmosphere, and can amount to several megawatts of wasted power. Furthermore, they are a local nuisance to radio transmission and can produce a noticeable hum.

Centralized power production has advantages of economies of scale and special resource availability (for instance, hydro resources), but centralized power requires long-distance transfers of power both to reach customers and to provide interconnections for reliability. Long distances are most economically served at high voltages, which require large-scale equipment and impose a substantial footprint on the corridors through which power passes. The most visible components of the transmission system are the conductors that provide paths for the power and the towers that keep these conductors at a safe distance from each other and from the ground and the natural and built environment. Common elements that are generally less visible (or at least more easily overlooked) include the maintained ROW along the path of the towers, access roads needed for maintenance, and staging areas used for initial construction that may be restored after construction is complete. Also visible but less common elements along the corridor may include

Fundamental Concepts of Electrical Power Transmission

Voltage, current, power, and electrical energy are some of the most frequently used terms when discussing transmission line characteristics.

Voltage. The voltage of a transmission line determines the line's ability to transmit electricity. This electric force, or electric potential, is measured in volts (V), or more typically in kilovolts (kV); 1 kV = 1,000 V.

Current. The current through a transmission line is a measure of the amount of electricity that is moving through a conductor. Current flow through a conductor is measured in amperes (amps).

Power. Power flowing through a power station is measured in watts (W), or more typically megawatts (MW), where 1 MW = 1,000,000 W. Power (more accurately, complex power) in an alternating-current system depends on the system voltage and current flow and is comprised of two components: real power and reactive power. If a small circuit has no reactive components (like these found in motors or computer power supplies) and is purely resistive (like those of an incandescent light bulb or toaster), then all power transferred through the circuit is real power (i.e., pure MW). Once a motor, for example, is added to a circuit, a reactive power component (measured in megaVARs [MVAR], for megavolt-amps reactive) is introduced along with the real power component. Both aspects of complex power are present and important in transmission system operations, and the respective amount of each is related to the line's power factor. Unfortunately, real power is often used synonymously for complex power. This simplification neglects the effects that reactive power can have on system stability and system operation.

Electrical energy. Energy is a measure of the ability to do work. The energy required by a load or provided by a generator is the product of power and time, and is usually expressed in kilowatt hours (kWh).

switching stations or substations, where lines of similar or different voltages meet to transfer power.

1.2 NORTH AMERICAN TRANSMISSION GRID

The interconnection of generating stations that started in the early years of the electricity industry continued as capacity grew, eventually evolving into what is known as the North American Transmission Grid. As it stands, this grid was not intended for the long-term transfer of large blocks of power. Historically, utilities planned capacity expansions so that they would be self-sufficient. Imports through interconnections with other utilities were short-term solutions for outages or other upset conditions. Most of the capacity of interties was reserved to maintain reliability in the face of such unplanned events. The use of interties for long-term inter-utility power transfers began to grow in the 1980s due to regional imbalances in generating capacity and power demand. The favorable economics for nonutility generators also promoted this trend for increased power transfers, or "wheeling." As a result, some expansion in the transmission infrastructure occurred, transmission line loading increased, and transmission lines were typically operated with higher loadings than in the past. Persistent regional imbalances involving fuel resource location, demand concentration, and environmental constraints are expected to increase reliance on the transmission grid for routine power transfers. Regulatory changes that allow purchasers to contract for power requirements with remote suppliers have been increasing transmission demands for some years (EIA 2000). This increased transmission system usage has lead to small transmission system transfer capability margins and has compromised the operating reliability of our nation's power grid. These factors are expected to require continued expansion of the North American Transmission Grid (Incentives Research, Inc. 1995). Resolving these transmission issues is not straightforward and is further compounded by complex siting and regulatory issues that are not easily overcome (NCEP 2006).

The North American electric system includes power generation, storage, transmission, and distribution facilities in Canada, the United States, and northern Mexico (Baja Norte). The first commercial power station was opened in 1879 in San Francisco, one year after the founding of the Edison Electric Light Company in the United States and American Electric and Illuminating in Montreal. In 1901, the first transmission line between the United States and Canada was opened at Niagara Falls. In 1905, work began on the Great Southern Grid. By 1914, that grid provided electricity transmission in North and South Carolina, Georgia, and Tennessee. In 1922, the Connecticut Valley Power Exchange pioneered utility interconnections. The first regional power pool, the Pennsylvania–New Jersey–Maryland Interconnection, was opened in 1927. As the extent of utility interconnections increased, so did the highest voltages employed for transmission. Figure 1.2-1 summarizes the history of peak transmission voltages according to their year of introduction.

The single most important parameter defining an electric power system is the peak electrical demand. This peak demand determines the necessary reliable generating capacity and the minimum capacity of the transmission and distribution systems. The peak demand is the instantaneous demand that occurs during a specified time period. Normally, peak demand is specified separately for the summer and winter seasons. Some regions have a higher summer peak demand, while others have a higher winter peak demand. The peak summer demand on the entire North American system was approximately 817,000 MW in 2004. The peak winter demand was 716,000 MW. At the time, there was approximately 20% excess generating capacity, for a total of 990,000 MW in 2004. The bulk transmission system operating between 115 and 765 kV delivers this power to distribution systems, with more than 207,200 miles of transmission lines operating at voltages higher than 230 kV. The distribution of demand, capacity, and circuit miles by national boundaries is summarized in Table 1.2-1.

For the power system, interconnection boundaries within the North American electric system are more important than the political boundaries. These interconnection boundaries separate the system into the Eastern, Western, and Electric Reliability Council of Texas (ERCOT) Interconnections. The ERCOT Interconnection is limited to Texas and covers most of that state. The Rocky Mountains separate the Eastern Interconnection from the Western Interconnection. The Western Interconnection serves 12 western states and 2 western provinces. Within each interconnection, all electric utilities are interconnected and operate synchronously; that is, the generators are operated such that the peak voltage from all generators occurs simultaneously. Voltage from alternating current (AC) generators varies sinusoidally reaching a

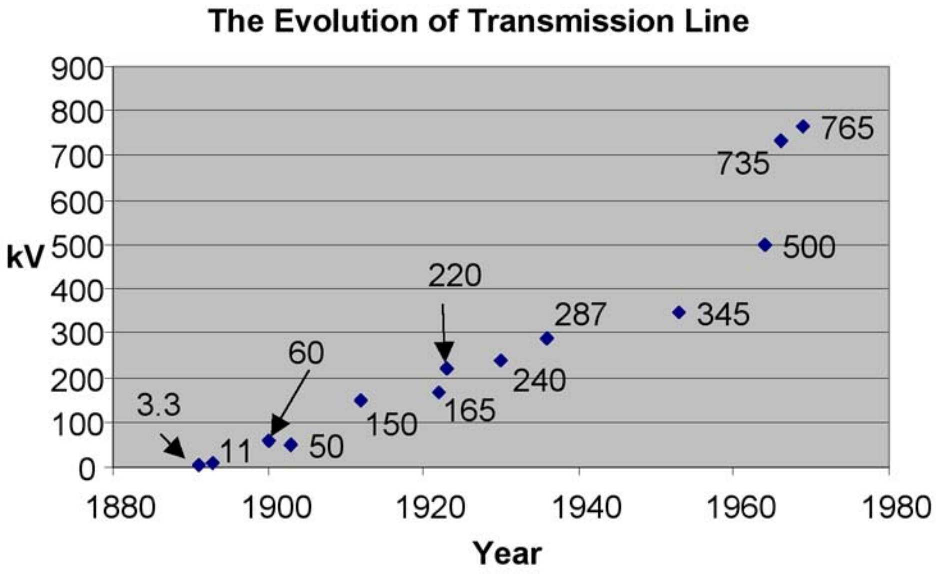

FIGURE 1.2-1 The History of Peak Transmission Line Voltage (Source: Data from EIA 2000)

TABLE 1.2-1 North American Electric Power Network by National Boundaries

	48 States	Canada	Baja Norte
Summer peak, MW	745,000	70,000	2,000
Winter peak, MW	622,000	92,000	2,000
Capacity, MW	893,000	95,000	2,000
Circuit miles >230 kV	160,000	46,600	600

Source: Johnson (2004).

peak or minimum 60 times per second. If generators were not “in phase,” the voltage from one would cancel some of the voltage from others. The distribution of demand, capacity, and circuit miles by interconnection is provided in Table 1.2-2.

These three major interconnections are connected to one another by a few direct current (DC) lines. The use of direct current avoids the need to synchronize the interconnections. On one side of the DC tie, current from the interconnection is converted from AC to DC. On the other side, it is converted from DC to AC such that it is in phase with the receiving interconnection. The ERCOT Interconnection is linked to the Eastern Interconnection via two DC lines having a total capacity of 800 MW. A total of eight ties with a capacity of 1,400 MW connect the Eastern and Western Interconnections. The ERCOT and Western Interconnections are not linked.

TABLE 1.2-2 North American Electric Power Network Characteristics by Interconnection

	Interconnection		
	Eastern	Western	ERCOT
Summer peak, MW	610,000	143,000	63,000
Capacity, MW	725,000	188,000	79,000
Circuit miles > 230 kV	130,000	70,000	8,000

Source: Johnson (2004).

1.3 RELIABILITY AND CONGESTION ISSUES

1.3.1 Transmission Constraints and Their Effects on Operations and Reliability[2]

As the transmission system has expanded over the years, surplus capacity available on transmission lines always seems to be consumed as the system grows or as transmission users find more economical ways of meeting system demands. Expansion leads to more usage that leads to more expansion. Transmission congestion results when a particular electricity transmission path cannot accommodate increased power flow. Although the reasons for congestion vary, the common consequence is that increased power flow on a particular transmission path is not possible without risking system reliability. This section identifies some of the common types of constraints and introduces some of the electrical phenomena associated with these issues.

1.3.2 Thermal Constraints

Line sag caused by exceeding a transmission line's thermal limit can result in a line fault, which is an arc between the transmission line and nearby vegetation, structures, or ground. When line faults occur, protective transmission line components remove the line from service to protect terminal equipment from serious damage. Once the faulted line is removed from service, other transmission lines in the system experience increased loads as they compensate for loss of the faulted line. Overloading can then occur on these transmission lines, which might exceed thermal operating constraints. If not controlled promptly, additional transmission line faults may occur. To ensure reliable system operation, a thermal operating constraint (specified in real power, or megawatts) is often placed on troublesome transmission lines to control the permissible power transfer across the lines. This limit establishes an upper bound on a particular line's transfer capability. It is important to note that in some cases, the transfer limit set on a particular line may

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[2] This section is largely a summary of portions of the Energy Information Administration (EIA) publication *Upgrading Transmission Capacity for Wholesale Electric Power Trade* (EIA 2002). The scope, organization, and conclusions of the original document are reflected here.

actually minimize the overheating of a different transmission line. Transmission line additions tend to alleviate the potential for exceeding transmission line capacity limits, at least until future uses of the additional transfer capacity are discovered and new limiting factors are reached.

System operators understand that, as a short-term workaround, the thermal limit may be exceeded in emergency situations. For this reason, transmission lines may also carry an emergency rating subject to a length of time that permits a higher transfer limit as long as the length of time the transfer is in effect does not exceed the specified period, for example, a 10-min emergency rating. In general, thermal constraints are more common in areas where the transmission system is tightly interconnected (shorter lines), such as within the Eastern Interconnection (Burgen 1986).

1.3.3 Voltage Constraints

Primarily as a result of transmission line reactance, the voltage at the receiving end of a conductor will be less than the voltage applied on the sending end. Large voltage deviations either above or below the nominal value may damage utility or customer equipment. Therefore, operating voltage constraints are employed to preserve operating conditions that meet necessary voltage requirements. In general, voltage constraints are more typical in areas where transmission lines are sparse and long, such as in the Western Interconnection (Burgen 1986). It may be more economical to address voltage constraints by modifying existing lines, such as adding capacitance, rather than by adding new transmission capacity.

1.3.4 System Operating Constraints

1.3.4.1 Parallel Flows

System operators can estimate the impacts of contract flows (those flows defined as point-to-point transactions) on parallel paths in the transmission system. These estimates allow operators to adjust contract schedules to minimize the likelihood of encountering a transfer limit on system transmission lines caused by loop flows. Therefore, specific operating constraints may be in place to mitigate the effects of parallel path power flows.

1.3.4.2 Operating Security

To ensure system operating reliability, an industry-derived set of standards and procedures has been recommended by the North American Electric Reliability Council (NERC). These recommendations suggest, for example, that the system should be operated so that it remains reliable in spite of disruption of a single system component (e.g., loss of one generator or loss of one transmission line). As a result, NERC operating guides tend to limit the maximum allowable operating capacity of a transmission line to a value less than its actual thermal limit to ensure available capacity in the event of a nearby transmission line outage. Similarly, NERC guidelines call for a generation margin to assure that sufficient generation remains on-line in the event of a generator outage. Likewise, operating guides exist to limit system effects caused by other types of conditions that affect system stability. All of these operating conditions are recommended as a means to improve overall system reliability while underutilizing specific system components. In addition, all system operators follow preventive operating guidelines to assure overall system integrity and reliability.

1.3.4.3 System and Voltage Stability

Because loads constantly change, small variations in frequency occur as the mechanical power at generator turbines adjusts to variations in electrical power demand. As long as frequency variations are small (i.e., small-signal stability), the interconnected system remains synchronized. The system will continue to operate in a stable manner unless the variations continue to gain in magnitude and oscillate at low frequencies. These oscillations can lead to more threatening voltage and frequency problems that may lead to instability and potentially to cascading outages.

Larger oscillations occur when system components are removed from service because a fault or disruption occurs. For example, frequency variations caused by a generator that goes off-line tend to be larger in magnitude than small-signal oscillations caused by load variations. Larger frequency swings provide more potential for uncontrolled swings that could lead to steady-state instability. Preventative measures are needed to minimize the likelihood of system instability, which could lead to widespread system outages. A system that lacks transient stability can produce these operating characteristics if corrective measures are not exercised to eliminate the condition.

Voltage instability occurs when the transmission system is exposed to large reactive power flows. As previously described, large reactive power flows on long transmission lines result in voltage drops at the receiving end of the line. Lower voltage causes increased current, which causes additional reactive losses. The end result is voltage collapse, which can damage equipment and cause additional outages, if left unresolved.

In general, long transmission lines are stability limited, not thermally limited (Burgen 1986). Generally, depending on the system conditions, equipment enhancements to add more reactive power or additional transmission lines can relieve steady-state and voltage stability problems.

1.4 ALTERNATIVES TO TRANSMISSION LINE EXPANSION

The addition of a new transmission line is not the only way to relieve power transfer constraints. There are a variety of approaches that may provide incremental improvements to transfer capability (with benefits anywhere from a few percent to doubled capability). Transmission owners are aware of these options and would consider the most cost-effective

Technical Limits to Power Transfers

Conductor resistance, temperature rating, and line sag. As a transmission line receives power, resistance inherent in the line conductor material converts some of the electrical energy into thermal energy, thereby increasing the line temperature. Line temperature increases as the current flowing through the line increases. Power transfers above a predetermined safe operating transfer limit can cause excessive conductor temperature, which causes line conductors to expand in length. Also, excessive operating temperatures may weaken the conductor, reducing its expected life. For underground conductors, high operating temperatures can damage insulation. Because aboveground transmission lines are suspended on fixed-distance tower structures, an expanding conductor manifests itself as sagging that reduces conductor distance to ground at the midpoint between towers. Because of line weakness at higher temperatures, this sagging can become permanent.

Voltage drop. The voltage drop increases as transmission line length increases. Similarly, the terminating voltage at the receiving end may vary above or below the recommended or nominal operating voltage, depending on the types of loads connected to the receiving end. Voltage constraints define the criteria needed to maintain receiving-end voltages within specified bounds (usually ± 5% of the nominal voltage). Customer and utility equipment operates most efficiently when operated near the nominal voltage level.

Parallel flows. Because the electric power grid provides an interconnected set of transmission lines, the flows that one might expect to occur over the transmission line that directly connects Area A to Area B actually occur over all of the interconnected lines in varying amounts. It may be true that the direct line may transfer most (perhaps 60%) of the power from Area A to Area B, but lines that are parallel to the direct line will also carry some portion of the power between the areas. Because electric power does not flow between areas in a simple manner that follows the contract path, the presence of parallel flows can cause a violation of thermal constraints on other lines in the system.

Synchronization. When two or more generators operate using the same interconnected transmission system, the generators must be synchronized. In the United States, this frequency is very near 60 hertz. Assuring synchronization maximizes power transfers and minimizes utility and customer equipment damage. In addition, synchronization helps to avoid transient instability and small-signal instability.

Source: EIA (2002).

option prior to suggesting the construction of a new transmission line in a new corridor. Below is a summary of these alternatives (EIA 2002).

1.4.1 Permit Higher Line Operating Temperatures

Although not generally recommended for extended periods of time, higher line operating temperatures may be permissible as line ratings are increased. However, increased sag and insulator integrity may be compromised. This alternative should be used with caution and should not be viewed as a permanent solution to a thermal line limit.

1.4.2 Improve Transmission Line Real-Time Monitoring

The actual temperatures occurring on transmission lines depend on the current, as well as on ambient weather conditions, such as temperature, wind speed, and wind direction. Because the weather affects the dissipation of heat into the air, an effort to monitor environmental conditions can result in higher line loading, if ambient conditions permit. When actual monitored values are used to establish line ratings, generic ratings based on nonspecific environmental conditions that are often very conservative can be avoided.

1.4.3 Uprate Substation Equipment

Just as thermal limits define maximum current flow values on transmission lines, equipment located at the terminating ends of a transmission line also have maximum current limits. In some situations, the limiting capacity may be linked to the equipment capabilities at the substation and not to the transmission line. If this is the case, the equipment at the substation can be replaced with larger components to increase the effective transfer limit of the line and its associated equipment.

1.4.4 Reconductor Existing Transmission Lines

To mitigate underrated transmission lines, the actual line conductors can be replaced with larger conductors to increase the transfer limit of the transmission line. Sometimes, multiple conductors are bundled together to obtain this improvement. As long as existing tower structures are adequate to support the additional weight of the new conductors, this alternative is useful to increase transfer capability. In some situations, this alternative may be cost-effective even when tower structures and insulators require modifications.

1.4.5 Install Phase-Shifting Transformers

As previously indicated, loop flows can have a significant effect on designated transfer limits. One method to reduce loop flows uses phase-shifting transformers to help direct flows to transmission lines with sufficient transfer capability. As a result, transfers that take place on transmission lines that are not part of the primary flow path are lessened so that transfer limit violations are not attained. Although phase-shifting transformers are costly and consume additional energy, they are widely used in the western United States.

1.4.6 Install Capacitors for Reactive Power Support

In situations where voltage support is problematic, capacitor banks can be used to increase the reactive power at a system bus to return voltage levels to nominal operating values. This method of increasing reactive-power support is often used to minimize voltage support problems and improve system stability.

1.4.7 High-Temperature Superconducting Technologies

Although mostly used for underground transmission line applications, more transmission line applications are using high-temperature superconducting methods. Although upgrades that use superconductors may be more costly, the method is most useful in areas were new ROWs are not available and existing conduits must be used.

1.5 TRANSMISSION LINE DESIGN SPECIFICATIONS

The towers and conductors of a transmission line are familiar elements in our landscape. However, on closer inspection, each transmission line has unique characteristics that have correspondingly unique implications for the environment. In this section, we list design specifications (line characteristics) that are commonly required to define a transmission line. Many of these specifications have implications for the net environmental effects.[3] For the purpose of this report, a range of values is considered for these specifications, with the exception that a fixed nominal voltage of 500 kV is assumed.

1.5.1 Overall Descriptive Specification

The most basic descriptive specifications include a line name or other identifier, nominal voltage, length of line, altitude range, and the design load district. The line identifier is commonly taken from endpoint names, e.g., Inland–Macedonia on the Cleveland Electric Illuminating Co. system. The endpoint names are generally geographic points, but may be substation names or major industrial facilities. The nominal voltage is an approximation to actual line voltage that is convenient for discussion. Actual voltage will vary according to line resistance, distance, interaction with connected equipment, and electrical performance of the line. For AC lines, the nominal voltage is close to the RMS (root mean square) voltage.[4] The altitude range is a rough surrogate for weather and terrain. This is important, since nearly all aspects of line design, construction, and environmental impacts are linked to weather. The design load district is another surrogate for weather. These districts are defined by the National Electrical Safety Code (NESC) and by some local jurisdictions. These districts include NESC Heavy Loading, NESC Medium Loading, NESC Light Loading, California Heavy Loading, and California Light Loading. The design wind and ice loading on lines and towers is based on the design load district. This affects insulator specifications as well as tower dimensions, span lengths, tower design, and conductor mechanical strength and wind dampening.

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[3] This information is extracted from utility survey results collected for the Electric Power Research Institute, Inc. (EPRI 1982).

[4] Taking the square of the voltage eliminates the sign change present in alternating current. The average of this positive value is then the square of the average voltage without regard to sign. RMS is the square root of this average. Thus, it is a good representation of the voltage supplied to a load.

1.5.2 Tower Specifications

The towers support the conductors and provide physical and electrical isolation for energized lines. The minimum set of specifications for towers are the material of construction, type or geometry, span between towers, weight, number of circuits, and circuit configuration. At 500 kV, the material of construction is generally steel, though aluminum and hybrid construction, which uses both steel and aluminum, have also been used. The type of tower refers to basic tower geometry. The options are lattice, pole (or monopole), H-frame, guyed-V, or guyed-Y. The span is commonly expressed in the average number of towers per mile. This value ranges from four to six towers per mile. The weight of the tower varies substantially with height, duty (straight run or corner, river crossing, etc.), material, number of circuits, and geometry. The average weight of 670 towers for 500-kV lines included in the EPRI survey (EPRI 1982) is 28,000 lb. The range of reported tower weights is 8,500 to 235,000 lb. The type of tower (specific tower geometry) is very site-dependent, and, for any given conditions, multiple options are likely to exist. The next section provides some illustrations of specific tower types and describes their relative impacts. The number of circuits is generally either one or two. The circuit configuration refers to the relative positioning of conductors for each of the phases. Generally the options are horizontal, vertical, or triangular. The vertical orientation allows for a more compact ROW, but it requires a taller tower.

1.5.3 Minimum Clearances

The basic function of the tower is to isolate conductors from their surroundings, including other conductors and the tower structure. Clearances are specified for phase-to-tower, phase-to-ground, and phase-to-phase. Phase-to-tower clearance for 500 kV ranges from about 10 to 17 feet, with 13 feet being the most common specification. These distances are maintained by insulator strings and must take into account possible swaying of the conductors. The typical phase-to-ground clearance is 30 to 40 feet. This clearance is maintained by setting the tower height, controlling the line temperature to limit sag, and controlling vegetation and structures in the ROW. Typical phase-to-phase separation is also 30 to 40 feet and is controlled by tower geometry and line motion suppression.

1.5.4 Insulators

Insulator design varies according to tower function. For suspension towers (line of conductors is straight), the insulator assembly is called a suspension string. For deviation towers (the conductors change direction), the insulator assembly is called a strain string. For 500-kV lines, the insulator strings are built up from individual porcelain disks typically 5.75 inches thick and 10 inches in diameter. The full string is composed of 18 to 28 disks, providing a long path for stray currents to negotiate to reach ground. At this voltage, two to four insulator strings are commonly used at each conductor connection point, often in a V pattern to limit lateral sway.

1.5.5 Lightning Protection

Since the towers are tall, well-grounded metallic structures, they are an easy target for lightning. This puts the conductors, other energized equipment, and even customer equipment at high risk. To control the effects of lightning, an extra set of wires is generally strung along the extreme top points of the towers. These wires are attached directly to the towers (no insulation), providing a path for the lightning directly to and through the towers to the ground straps at the base of the towers. The extra wires are called shield wires and are either steel or aluminum-clad steel with a diameter of approximately ½ inch.

1.5.6 Conductor Motion Suppression

Wind-induced conductor motion, aeolian vibration, can damage the conductors. A variety of devices have been employed to dampen these oscillatory motions. By far, the most common damper style on 500 kV lines is called the Stockbridge damper. These devices look like elongated dumbbells hung close to and below the conductors, a few feet away from the point of attachment of the conductors to the tower. The weighted ends are connected by a short section of stiff cable, which is supported by a clamp to the conductor immediately above. Dampers can prevent the formation of standing waves by absorbing vibrational energy. Typically, a single damper is located in each span for each conductor.

1.6 TRANSMISSION LINE COMPONENTS

1.6.1 Towers

Transmission towers are the most visible component of the bulk power transmission system. Their function is to keep the high-voltage conductors separated from their surroundings and from each other. Higher voltage lines require greater separation. The unintended transfer of power between a conductor and its surroundings, known as a fault to ground, will occur if an energized line comes into direct contact with the surroundings or comes close enough that an arc can jump the remaining separation. A fault can also occur between conductors. Such a fault is known as a phase-to-phase fault. The first design consideration for transmission towers is to separate the conductors from each other, from the tower, and from other structures in the environment in order to prevent faults. This requirement and the electrical potential (voltage) define the basic physical dimensions of a tower, including its height, conductor spacing, and length of insulator required to mount the conductor. Given these basic dimensions, the next design requirement is to provide the structural strength necessary to maintain these distances under loading from the weight of the conductors, wind loads, ice loading, seismic loads, and possible impacts. Of course, the structure must meet these requirements in the most economical possible manner. This has lead to the extensive use of variants on a space frame or truss design, which can provide high strength with minimal material requirements. The result is the ubiquitous lattice work towers seen in all regions of the country. The last design requirement is to provide a foundation adequate to support the needed tower under the design loads.

Some of the environmental implications of a transmission line result directly from these transmission tower design requirements. First, the physical dimensions of the towers and the resulting line arrangements and line spacing establish the necessary minimum dimensions of the ROW, including clearances to natural and man-made structures. To create and maintain these clearances, it is often necessary to remove or trim vegetation during construction and operation. In addition, excavation, concrete pouring, and pile driving are required to establish foundations. All of these tasks require access roads and service facilities with dimensions and strength sufficient to handle large, heavy tower components, earthmoving equipment, and maintenance equipment.

Figure 1.6-1 shows a lattice-type tower with a single-circuit 765-kV line. A close look at the figure reveals twelve conductors strung from insulators suspended on the crossbar, but this is a single-circuit line. A single-circuit AC line transfers power in three phases. The voltage in each phase varies sinusoidally with a period of 1/60 second, and each of the phases is separated from the others by 120 degrees. Thus, there are three isolated conductors for a single AC transmission circuit. In addition, some high-capacity circuits at up to 345 kV use multiple (bundled) conductors for each phase rather than a single larger conductor. The lattice tower in Figure 1.6-1 uses groups of four conductors to carry each of the three phases. Above 345 kV, bundled conductors are normally used to reduce corona discharge.

There are several other features to note in Figure 1.6-1. The conductors are supported in a horizontal configuration. This configuration requires broad towers to achieve adequate line separation, which is about 45 feet between conductors for 765 kV. The horizontal configuration requires a correspondingly greater cleared width for the ROW than a vertical configuration,

FIGURE 1.6-1 Lattice (left) and Monopole (right) Towers (Source: Argonne Staff Photo)

which stacks the conductors in a vertical plane. The vertical configuration results in higher, narrower towers. An alternative to the lattice tower, the monopole tower, is also used in this power corridor. In this case, the monopole supports much lower-voltage conductors for distribution to industrial customers and substations. Thus, the size comparison suggested in the figure is not valid. Still, monopole towers can be used for transmission-level voltages and do reduce the apparent footprint of the towers.[5] The monopole structures shown here actually support two circuits of three conductors each, for a total of six isolated conductors. Just barely visible at the top outer edges of these towers are grounding lines that are connected directly to the towers and that serve as lightning protection. Finally, it is important to recognize that Figure 1.6-1 represents an important type of shared energy corridor, a power corridor with multiple circuits supported on separate towers. Because of spacing requirements to avoid faults, substantial width is required to separate the tower lines. This is discussed further in Section 1.6.4. Figure 1.6-2 shows another example of a shared corridor. Here, a high-voltage distribution line is flanked by much higher-voltage transmission lines. Note that the lattice towers each carry two (three-phase) circuits in a vertical configuration and that single rather than bundled conductors are used. The point of view of the photograph obscures the fact that the lattice towers are twice the height of the wood pole structures.

FIGURE 1.6-2 Multiple Lines in a Power Corridor (Source: Argonne Staff Photo)

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[5] Monopole construction requires deeper foundations with greater mass than the lattice towers, which generally rest on smaller foundations set only at each corner. Thus, for a smaller visual footprint, more excavation and concrete work may be required.

A typical transmission tower height for the horizontal configuration is 100 feet. The tower is designed to bear the vertical load of the conductor weight and horizontal loads from wind against the towers and the conductors. In long straight runs, the horizontal load from the conductor tension is balanced by lines going in opposite directions. However, where a change of direction is required, the conductor tension is unbalanced and a stouter tower, called a deviation tower, is required. This tower is likely to have a broader footprint than the other towers. Figure 1.6-3 shows a 765-kV deviation tower located less than 50 yards from a new two-story home. The illustration provides a good indication of the size of these towers. The footprint for towers along straight segments is smaller because the balanced conductor load reduces the bending moment that must be supported at the foundations.

FIGURE 1.6-3 Deviation Tower in a Residential Neighborhood (Source: Argonne Staff Photo)

1.6.2 Conductors

A variety of conductor compositions and constructions are currently in use to meet a variety of specific requirements. In the early years of the industry, copper was used almost exclusively because of its high electrical conductivity, but cable diameters with copper were determined more by the need for mechanical strength than by the need for improved conductivity. The low strength-to-weight ratio of copper limited the acceptable span length (distance between towers). Aluminum, with its higher strength-to-weight ratio, was introduced as an alternative to copper, allowing for greater span lengths. Though copper has higher conductivity than aluminum, the lower density of aluminum gives it a conductivity-to-weight ratio twice that of copper. The first aluminum transmission lines were installed in the last 5 years of the 19th century (Thrash 2003). An additional incentive favoring aluminum conductors in more recent times is that aluminum is more economical to use than copper, even though aluminum has only 60% of the conductivity of copper. Typical aluminum conductors are composed of multiple 1/8-inch-thick strands twisted together. There are about 50 varieties of multistrand conductor cables, which are named after flowers (Hayes 2005), perhaps because the cross sections suggest flower-like patterns and symmetry. The Narcissus is a 61-strand conductor that can carry over 1,100 amperes.

In 1907, aluminum-steel composite cables were introduced (Thrash 2003) to achieve an even higher strength-to-weight ratio while maintaining the electrical performance of aluminum. These cables have a central core of steel strands surrounded by aluminum strands. While steel is relatively poor conductor, its high strength makes it possible to increase span lengths, which reduces tower investments. These composite conductors are designated by stranding combinations. For instance, 84/7 has 84 aluminum strands surrounding a central core of 7 steel strands. These aluminum conductor steel reinforced (ACSR) composite conductors have been given bird names, rather than flower names. For example, the 26/7 ACSR conductor is known as the Starling.

Very recently, a new type of composite using ceramic fibers in a matrix of aluminum has been introduced that has lighter weight and higher strength. These ACCR cables (aluminum conductor composite reinforced) were the first technology tested at the Electric Power Research Institute’s Powerline Conductor Accelerated Testing Facility, which opened in 2003. Frost & Sullivan has reported that in 2005 the North American ACCR market had already earned $25 million, and it has projected a market of $225 million by 2012 (NewswireToday 2006). This new conductor format has the advantage of high strength even at elevated temperatures, and the addition of zirconium to the aluminum alloy makes it more resistant to degradation at high temperatures.

1.6.3 Substations

As indicated, the voltage required for economical transmission of electric power exceeds the voltage appropriate for distribution to customers. First, customer equipment generally operates at only a few hundred volts, rather than at the hundreds of thousands of volts used for transmission. Second, if high voltages were maintained up to the point of customer connection, fault protection would be extremely expensive. Therefore, distribution from the transmission line to customers is accomplished at much lower voltages, so transformers are required to reduce voltage before the power is introduced to a distribution or subtransmission system. These transformers mark the end of the transmission line and are located at substations. Each transmission line starts from an existing substation and ends at a new substation. If the new transmission line were high-voltage direct current (HVDC), the origin substation would be expanded to accommodate AC-to-DC converters. Intermediate substations may also be required if there is a voltage change along the route, say, from 500 kV to 230 kV. Figure 1.6-4 shows a Midwestern substation that supplies a 765-kV long-distance transmission line from 345-kV feeders connected to area power plants. The site occupies approximately 10 acres.

Figure 1.6-5 shows a substation of comparable size under construction. This substation, which is now complete, is the terminus of a 500-kV, 600-MW line in the Bonneville Power Authority System.

1.6.4 ROWs

A ROW is a largely passive but critical component of a transmission line. It provides a safety margin between the high-voltage lines and surrounding structures and vegetation. The ROW also provides a path for ground-based inspections and access to transmission towers and other line components, if repairs are needed. Failure to maintain an adequate ROW can result in dangerous situations, including ground faults.

A ROW generally consists of native vegetation or plants selected for favorable growth patterns (slow growth and low mature heights). However, in some cases, access roads constitute a portion of the ROW and provide more convenient access for repair and inspection vehicles.

FIGURE 1.6-4 Substation in the Vicinity of Manhattan, IL (Source: Argonne Staff Photo)

FIGURE 1.6-5 Wautoma Substation under Construction (Source: BPA)

Table 1.6-1 shows the range of minimum ROW widths reported by U.S. utilities for various line voltages. The number of companies reporting each width provides an indication of the most common size ranges.

1.6.5 Multiple Lines

The use of a common corridor of ROW for multiple transmission lines is likely to be restricted if it presents a credible risk of a multicircuit outage. Mitigation measures, principally increasing line spacing beyond that required for fault protection, may be used to reduce risk. Multiple lines in a single corridor are subject to the following hazards[6]:

1. A tower from one line falling against conductors of an adjacent line.
2. A shield wire (grounded lightning protector connecting the tops of the towers) being dragged onto adjacent lines by an aircraft.
3. An aircraft damaging more than one circuit.
4. Fire or smoke on the ROW.
5. Lightning strikes.
6. Deliberate malicious damage.

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[6] Items 1 through 5 are from Appendix D, "Line Separation," of BPA (2003).

TABLE 1.6-1 Minimum ROW Widths

Voltage (kV)	Range of Widths (ft)	No. of Companies Reporting
<230	<50	51
	51 to 125	41
	>125	7
230	<75	40
	76 to 125	36
	>125	30
345	<75	6
	76 to 125	36
	>125	30
500	<125	4
	126 to 175	21
	>175	13

Source: FERC (2004).

A line separation of at least one span (perhaps 700 feet) has proven effective in avoiding multicircuit outages. A separation of 2,000 feet from adjacent 500-kV lines was planned for the Los Banos–Gates 500-kV line in California. This separation requirement implies a substantially wider ROW than would be required for electrical protection and line maintenance.

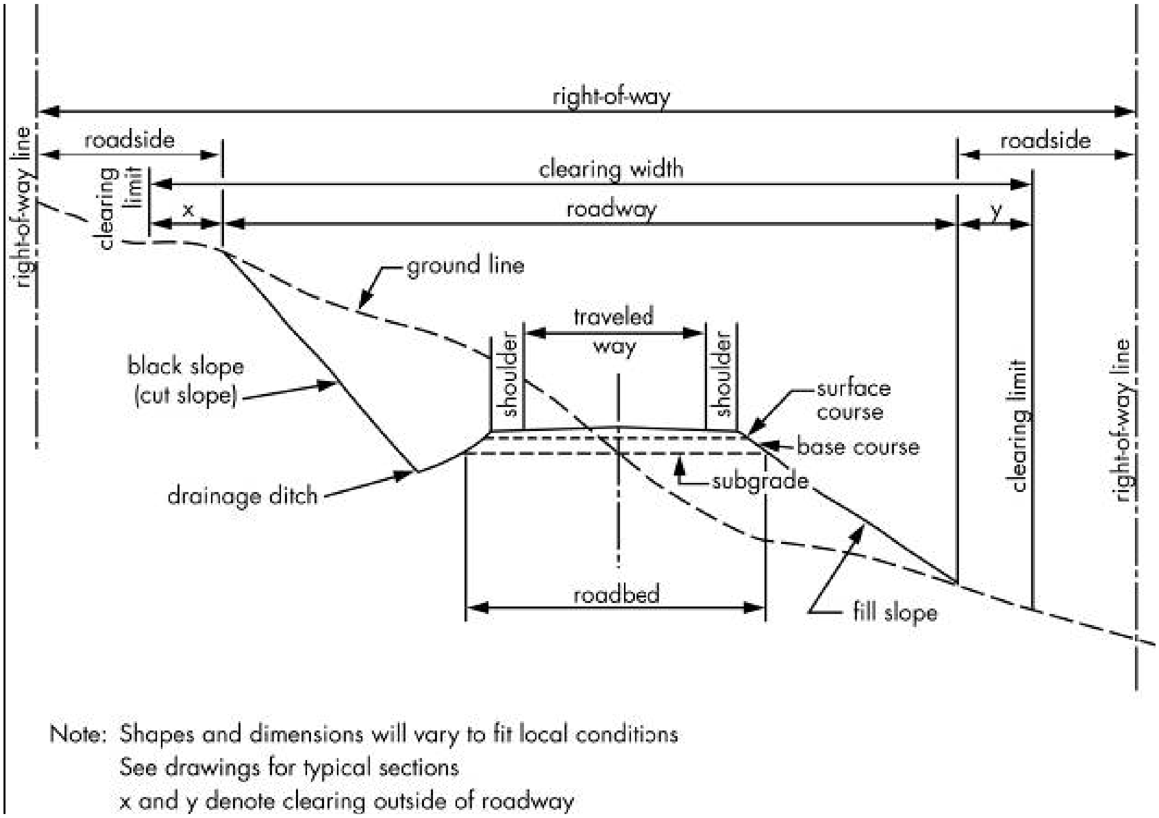
1.6.6 Access Roads

Access routes to transmission line structures for both line construction and maintenance use existing roads wherever possible. At least a portion of existing roads along the route is likely to be paved. New roads constructed for access would be gravel. From the perspective of environmental impacts, a third road type is “improved.” This refers to existing roads that need improvements in order to meet the loads expected for line construction and maintenance. Roads are also classified as temporary or permanent. A temporary road will be decommissioned after construction is complete, and the ROW will be restored. Thus, from an environmental effects perspective, there are five road types to be considered. These are displayed in Table 1.6-2. In what follows, we assume that all existing roads are permanent, and that existing roads that require improvements are gravel.

The roadway includes the traffic-bearing traveled way, the shoulders, and areas adjacent to the road that have been excavated or filled to provide drainage and support. Beyond the roadway are the clearing width and the outer boundary of the ROW. These features, which are shown in Figure 1.6-6, are important for estimating the environmental impact. Specifically, the design or stated road width likely understates the disturbed width.

TABLE 1.6-2 Access Road Types

New Roads		Existing Roads (permanent)		
Gravel		Improved	Serviceable	
Temporary	Permanent	Gravel	Paved	Gravel
Type I	Type II	Type III	Type IV	Type V



Note: Shapes and dimensions will vary to fit local conditions
See drawings for typical sections
x and y denote clearing outside of roadway

FIGURE 1.6-6 Commonly Used Terms in Road Design (Source: BLM and USFS 2006)

Access road widths (traveled way plus shoulders) are commonly from 12 to 14 feet. Tucson Electric Power (TEP) specified 12 feet in the Sahuarita-Nogales Environmental Impact Statement (EIS) (Office of Fossil Energy 2005). The Bonneville Power Authority (BPA) specified 14 feet in the Schultz-Hanford EIS (BPA 2003) with an exception for areas served by helicopters, where an access road width of 12 feet would be sufficient. The TEP report does not describe the roads in any more detail, but we might assume 5 feet on either side for drainage ditches. No additional cleared area is needed beyond the ditches. BPA assumed a 3-foot temporary disturbance on either side of the 14-foot road surface width. BPA further classified roads needing improvement into three categories according to the amount of improvement required.

1.7 CONSTRUCTION, OPERATION, AND MAINTENANCE

1.7.1 Construction Phase

1.7.1.1 Staging Area Development

Equipment and materials are stockpiled before and during construction in staging areas, which are normally adjacent to the ROW where they would not interfere with the movement of materials, erection of towers, and line pulling.

The staging areas are used for storage of materials and fuel used during construction, including diesel fuel, gasoline, lubricating oil, and paints. Depending on the location and stage of construction, they may be used for storage of herbicides that are used to maintain clearance along the ROW. Blasting agents may be stored at staging areas, subject to applicable regulations and standards. These include the federal requirements listed in Table 1.7-1.

Based on BPA practice, staging areas would be located every 8 to 10 miles. The size would vary, but 1 to 3 acres would accommodate materials and vehicle and equipment parking. Tower assembly areas are accounted for separately.

TABLE 1.7-1 Federal Explosives Storage Requirements

	Restrictions on Type 2 Outdoor Storage Facilities
Size	Shall be at least 1 cubic yard in size or securely fastened to a fixed object.
Ground	Outdoor storage facilities shall be supported in such a manner so as to prevent direct contact with the ground. Ground around storage facility shall slope away for drainage.
Construction	Sides, bottoms, tops, and covers or doors shall be constructed of .25-inch steel and lined with 2 inches of hardwood.
Unattended storage	Unattended vehicular storage facilities shall have wheels removed or shall be immobilized by kingpin locking devices.

Source: Rocketry Online (2000).

1.7.1.2 Establish Access

New Access Road Requirements. The extent of new access road construction that would be required to service construction and maintenance of a transmission line is very site-specific. Existing roads may serve some of the ROW, and some sections may be accessed only by air. To estimate a reasonable range of new road development, we have reviewed estimates for site-specific EISs for new transmission lines recently completed in the western United States. Note that fill material and road base are likely to be derived from local sources at sites known as borrow pits. Excavation of borrow pits removes material and possibly habitat from nearby land. These impacts can be minimized by restoration of the surface of the pits.

Four alternative routes were evaluated for the TEP Sahuarita-Nogeles transmission line, which is a 345-kV double-circuit line of about 60 miles in length. One route, the Eastern Corridor, was eliminated from consideration during the EIS process. The remaining routes were designated as the Western Corridor, Central Corridor, and Crossover Corridor. TEP stated that access to the ROW would rely on local paved roads, existing access roads, and new access roads. The estimated total length of each corridor and length of new access roads are listed in Table 1.7-2. Based on that data, the miles of new access road required per mile of corridor ranges from 0.18 to 0.29 miles.

Additional data was provided by the BPA EIS for the Shultz-Hanford corridor. For a total length of 63.7 miles, BPA anticipated the need for 18.0 miles of new access roads. However, BPA also anticipated the need for improvements to 56.3 miles of existing roads. The new road requirement corresponds to 0.28 miles per mile of corridor length, which is consistent with the TEP data. Improvements to existing roads were not mentioned in the TEP EIS. Using the BPA experience, 0.88 miles of road improvements is required per mile of line ROW.

Clearing of Sites for Structures. Figure 1.7-1 shows a site clearing operation during construction of a 500-kV line in hilly terrain. Specific sites for structures such as towers and substations (see Figure 1.7-2) must be cleared as well as the ROW, staging areas, and areas for tower assembly. Some estimates of the land area from other EIS analyses in the western United States are provided below along with discussion of more specific construction activities and techniques.

Clearing of the ROW can employ a variety of techniques, including the use of heavy equipment, such as dozers and scrapers, or selective hand-clearing. The choice depends upon topography, current growth, land use, and plant species on ROW-adjacent property and the presence of sensitive environments. In sensitive areas, hand-clearing may be used to minimize environmental disturbance. However, even with careful practices, habitat may be changed by ROW clearing, especially if it results in substantial changes to the original vegetation cover. Changes may extend to the area adjacent to the ROW, which is subsequently exposed to increased sunlight or other changes. This is particularly true in the case of an interruption in an otherwise continuous forest cover. Changes in drainage patterns may be an important consideration, especially if the ROW is adjacent to a body of water. Where a crossing is

TABLE 1.7-2 Corridor Length and Access Road Requirements for TEP Project

Corridor	Total Corridor Length, miles	New Access Roads, miles	New Road per Mile of Line
Western	65.7	18.8	0.29
Central	57.1	11.6	0.20
Crossover	65.2	11.6	0.18

Source: DOE (2005).

FIGURE 1.7-1 Clearing Vegetation for Expansion of Kangley-Echo Lake Substation (Source: BPA)

required, there is further risk of impact to the body of water and its aquatic species, since these are dependent on the bordering wetlands that must also be crossed. Erosion at the points of crossing introduce soil particles, increasing sedimentation and the associated clouding of water. The maintenance of a buffer zone between the ROW and the body of water is one strategy used to minimize impacts. Hand-clearing and the removal of slash (cuttings) from the water and the immediately adjacent shore are strategies to reduce construction impacts.

The brush and slash removed from the ROW must be disposed of by one of four methods: burning, piling, chipping, and leaving it where it falls (Berger 1995). Assuming that burning is controlled and regulated under conditions of very low fire hazard, it can leave the ROW in a favorable condition for certain species. Slash piles can obstruct vehicle and large-mammal movements, but do provide favorable conditions for smaller species and can serve erosion control when located in a gully or sloped terrain.

FIGURE 1.7-2 Site Preparation for Construction of Substation (Source: BPA)

TEP made the following assumptions for areas that must be cleared for tower assembly, tower construction, and conductor pulling (Office of Fossil Energy 2005):

1. Each tower would require a tower assembly area of 100 feet by 200 feet.

2. Lattice towers would require 80,000 square feet per tower for construction.

3. Monopole towers would require 31,415 square feet per tower for construction.

4. Tower construction area is reduced by 25% for impact calculations because of overlap with assembly area.

5. At any given time during construction, two cable-pulling sites of 37,500 square feet (150 feet × 250 feet) would be in use or in preparation.

1.7.1.3 Tower Construction

Figures 1.7-3–1.7-8 show various steps of the transmission tower construction process.

Note that this monopole footprint is smaller than that of a lattice tower, but the amount of concrete required is substantially greater to withstand the bending moment at the ground anchor.

FIGURE 1.7-3 Drilling Rock for Blasting to Set Tower Foundation Footings (Source: BPA)

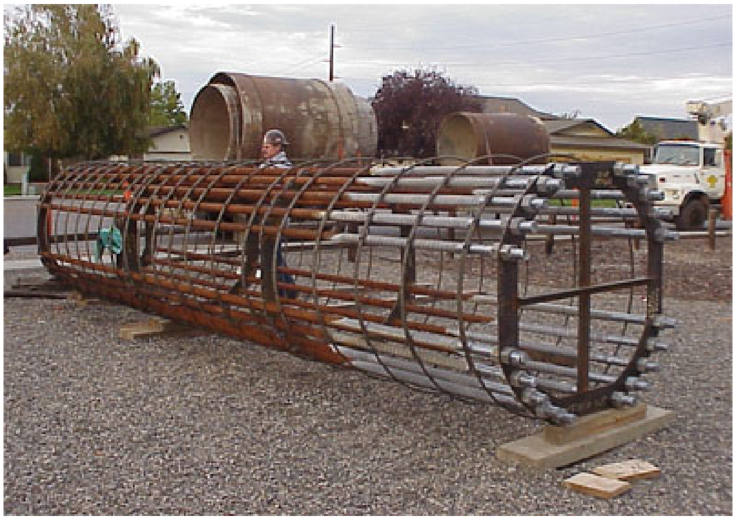


FIGURE 1.7-4 Anchor Bolt Cage and Reinforcing for Tower Foundation Construction (Source: BPA)

FIGURE 1.7-5 Anchor Bolt Cage in Place (Source: BPA)

FIGURE 1.7-6 Hole Being Drilled for Footing Leaves a Mound of Dirt, Rocks, and Clay (Source: BPA)

FIGURE 1.7-7 Helicopter Crane Being Connected to Tower Sections during Tower Assembly (Source: BPA)

FIGURE 1.7-8 A Crane Being Used to Lower a Tower Section onto a Tower Base (Source: BPA)

1.7.1.4 Substation Construction

Substation construction is expected to take 6 to 9 months and will cover approximately 10 acres for the fenced station plus 3 acres for construction support. Figure 1.7-9 shows a representative substation under construction.

FIGURE 1.7-9 Substation under Construction (Source: BPA)

1.7.1.5 Conductor Stringing

The process of attaching conductor wires to the insulators suspended from the towers is called conductor stringing. It generally involves pulling the conductor off of a truck-mounted spool. This process typically will not result in additional land disturbance beyond that required for tower construction. An exception may occur at diversion towers where severe line direction changes occur.

1.7.1.6 ROW Restoration

It is general practice to restore the ROW after construction, although the replacement of tall vegetation is not a part of restoration directly within the ROW boundaries. Tall vegetation can create ground-fault hazards, including the risk of fire. Plants consistent with native species are selected, although with consideration of their growth rates and mature plant heights. In some areas, the ROW must remain passable by land vehicles for line inspections.

1.7.1.7 Hazardous Materials

Table 1.7-3 lists hazardous materials that are typically used in transmission line construction.

TABLE 1.7-3 Hazardous Materials Typically Used for Transmission Line Construction

2-cycle oil (contains distillates and hydrotreated heavy paraffinic)
ABC fire extinguisher
Acetylene gas
Air tool oil
Ammonium hydroxide
Antifreeze (ethylene glycol)
Automatic transmission fluid
Battery acid (in vehicles and in the meter house of the substations)
Bottled oxygen
Brake fluid
Canned spray paint
Chain lubricant (contains methylene chloride)
Connector grease (penotox)
Contact Cleaner 2000
Diesel deicer
Diesel fuel
Diesel fuel additive
Eye glass cleaner (contains methylene chloride)
Gasoline
Gasoline treatment
Hot stick cleaner (cloth treated with polydimethylsiloxane)
Hydraulic fluid
Insect killer
Insulating oil (inhibited, non-PCB)
Lubricating grease
Mastic coating
Methyl alcohol
Motor oils
Paint thinner
Propane
Puncture seal tire inflator
Safety fuses
Starter fluid
Sulfur hexaflouride (within the circuit breakers in the substations)
Wasp and hornet spray (1,1,1 trichloroethene)
WD-40
ZIP (1,1,1-tricholorethane)
ZEP (safety solvent)

Source: SDGE (2006).

1.7.2 Operation and Maintenance Phase

1.7.2.1 Normal Operation

During normal operation, transmission lines require very little intervention. The only exception is periodic inspections and vegetation management, which are discussed below. Inspections are frequently done from the air using a small plane or a helicopter. However, tracked or other ground vehicles also have a role in line inspections, particularly where air inspections are unsafe or where a closer inspection of a potential hazard is required.

Table 1.7-4 summarizes survey data on the frequency of aerial and ground inspections. It is not clear how “as needed” is determined without inspections.

1.7.2.2 ROW Management

ROW maintenance is used to assure safe clearance between conductors and vegetation and to allow passage for inspections on foot or by vehicles. Vegetation management is a critical function. Failure to perform adequate vegetation management was a major contributing factor to the August 2003 blackout that affected much of the Northeast and Midwest. The combination of

TABLE 1.7-4 Number of Companies Reporting Various Inspection Frequencies

Frequency	Aerial	Ground
More than twice a year	25	7
Semiannual	34	22
Annual	46	76
Biennial	6	6
Every 3 years	1	6
Less than every three years	3	25
As needed	8	12
Did not report	38	7

Source: FERC (2004).

heavy electrical loads, high ambient temperature, and low wind speed allowed a critical line to sag close enough to a tree that a ground fault occurred. The subsequent system response resulted in the blackout. The difficulty is that vegetation management involves mechanical cutting and chemical herbicides. In some cases, it involves the replacement of native species with plants that have more favorable growth patterns. In some instances, utilities have reported improvements in local ecosystems due to careful ROW vegetation planning and maintenance.

Good vegetation management practice includes (1) the application of wire-zone, border-zone design concepts; (2) consideration of potential line sag and sway; (3) frequent inspections; and (4) public education (FERC 2004).

The wire-zone, border-zone concept requires differing maintenance practices across the width of the ROW. In the central section, or wire zone, relatively low vegetation heights are maintained by trimming, herbicides, or plant selection. Adjacent to this central section is the border zone, which can accommodate taller species and less aggressive maintenance. This can provide a transition to native plants outside of the ROW, which are not at risk of causing ground faults. Figure 1.7-10 shows a fire caused by a ground fault. The resulting high temperature can compromise the strength of towers and conductors, leading to mechanical failures.

1.7.2.3 Repairs and Repair Access

Although normal operation requires minimal intrusion into the ROW, line or tower failures can result in the reintroduction of heavy equipment, work crews, excavation, and materials transport.

FIGURE 1.7-10 Fire Caused by Ground Fault (Source: ESRI)

1.8 DESIGN FEATURES AS MITIGATION

Environmental impacts from the construction and operation of transmission lines can be reduced or minimized through careful consideration of a number of factors regarding the design of the overall transmission line project. These factors can be considered at three levels corresponding to the physical scale of the project: the overall route of the line; the placement of the ROW and line; and the design and construction of the transmission line structures. Design mitigation factors at each of these levels are discussed below.

1.8.1 Route Selection

Route selection is the most important design consideration for mitigating the impacts of electrical transmission lines. Route selection is generally highly constrained due to various competing factors, but, to the extent practical, should consider the following route selection factors that would tend to mitigate the impacts of the line:

- *Avoidance of sensitive habitats and wetlands*. If practicable, transmission lines should be routed so as to avoid crossing sensitive habitats. Such areas could be affected by the installation of temporary or permanent access roads and by the effects of clearing or controlling vegetation in the ROW. The latter effects would include increased sunlight on pools and wetlands, edge effects created along the cleared ROW, and ecological changes associated with changes in habitat and the presence of the transmission line structures.

- *Avoidance of sensitive areas*. Such areas as parks; wilderness, recreational, and scenic areas; Native American sites and burial grounds; and areas rich in cultural resources should be given special consideration in route selection and be avoided, if possible. Pristine wilderness areas are particularly sensitive to the visual and noise impacts of transmission lines and perhaps to increased vehicle traffic from access roads and the cleared ROW. Areas containing cultural resources can be impacted by the construction of the line or by increased accessibility to archeological sites by souvenir hunters.

- *Avoidance of farmland*. Farmland, particularly high-value farmland, and land with mobile irrigation equipment should be avoided if transmission structures would interfere with farm operations. In many cases, however, the presence of transmission line structures is quite compatible with farm operations, and ROW leases produce a welcome source of income to farmers.

- *Avoidance of historic buildings*. Buildings protected by the National Historic Preservation Act (NHPA) should be identified during route selection and avoided, if possible. The NHPA also protects certain cultural resources, such as those mentioned above.

- *Avoidance of residential areas*. The greatest consideration in route selection is typically required in regard to residential areas. Such areas are problematic because transmission lines typically terminate near residential areas and often must pass through them to reach substations serving population centers. Route selection should consider the shortest routes through residential areas and should choose routes with existing transmission lines or that are otherwise already similarly impacted to minimize additional impacts from the new line.

1.8.2 ROW Design

ROW design addresses the specific placement of transmission lines and considers such factors as the specific placement of the ROW within the selected route, ROW width, separation between multiple lines, separation between multiple transmission systems, access roads, vegetation clearance, and maintenance and management. ROW design should consider the following factors in the context of minimizing impacts:

- *Slopes*. The ROW for the transmission line should avoid steep slopes to the extent possible within the selected route. Steep slopes are susceptible to erosion and are difficult to restore after being disturbed.

- *Soil types*. ROW placement should be such that the locations of towers, access roads, and other facilities avoid unsuitable soils. Such soils are those that are easily eroded, difficult to restore, wet, or otherwise unsuited to the placement of transmission line structures.

- *Blasting requirements*. The ROW should be designed to minimize the amount of blasting that would be required to construct the transmission line, for example, by skirting rocky areas, where possible.

- *Visual impacts*. The placement of specific transmission line structures should consider visual impacts within the limits of the selected route. Consideration should be given to locations where the line is likely to be viewed, such as existing residences roads, and to sensitive locations such as river crossings and other recreational areas.

- *Sensitive habitats*. ROW placement should avoid wetlands, nesting sites, habitats of observed threatened and endangered species, and other sensitive locations, wherever possible.

- *Significant structures or locations.* Structures or locations that have historical or cultural significance or are of particular interest or importance for other reasons should be avoided.

- *Existing disturbed areas*. Existing roads, access roads, construction areas, or other already disturbed areas should be used, whenever possible.

- *Tower placement*. The placement of transmission line towers or other structures should be given special consideration near residences, wetlands, streams, and at river crossings, among other sensitive locations. The placement of the more massive corner and end towers should be given further consideration with respect to sensitive locations.

1.8.3 Transmission Line Design

Transmission line design addresses such factors as the type of support structures used, the materials used, the number and spacing of conductors, ground wires, any communication wires used, and line markers. The following factors should be considered in order to minimize impacts of the line:

- *Tower design*. A number of design choices must be considered in selecting the types of transmission towers used in constructing the transmission line with respect to various types and degrees of environmental impacts. Major design considerations include the selection of guyed versus freestanding towers, wood versus steel or weathered steel construction, monopole versus lattice structure, and the arrangement of conductors on towers.

- *Clearances*. Transmission line design factors such as the type of current carried, voltage, wattage, and conductor materials drive the specification of several design clearances. Such clearances include the spacing between conductors; vertical clearance to ground surface, accounting for line sag; horizontal clearances between the line and other electric lines; horizontal clearances between the line and aboveground and belowground pipelines; horizontal clearances between the line and nearby residences; and vertical and horizontal clearances between the line and vegetation within and adjacent to the ROW.

- *Specific mitigation features*. Several specific line design features can be used to reduce a variety of potential impacts, including the use of nonreflecting conductors and tower materials; the use of weathered steel instead of wood for tower structures; the use of raptor perches and raptor deflectors on towers; and the use of ball markers and flappers to reduce bird or airplane collisions with the line.

1.9 BEST MANAGEMENT PRACTICES

In addition to design factors, a large suite of best management practices (BMPs) have been established from past experience for avoiding, reducing, or minimizing impacts during the construction and operation of transmission line projects. BMPs involve the planning, execution, control, mitigation, and practice of activities involved in the construction, maintenance, and operation of a transmission line or other infrastructure projects. Some of the BMPs most typically applicable to transmission line projects are summarized below:

1.9.1 Preconstruction BMPs

A number of planning, surveying, and work preparation BMPs conducted prior to the start of work on a transmission line project should be implemented to avoid unnecessary impacts, including the following:

- Obtain permits for all activities that require them. Permits may be needed for clearing vegetation, using explosives, applying pesticides, reseeding disturbed areas, using fuels or hazardous materials, or working in and around wetlands and rivers.

- Train workers on ecological concerns and permit conditions prior to deploying them to the field.

- Identify sensitive areas and resources specified by permits or otherwise of concern through an inspection of the transmission line route and ROW.

- Perform ROW surveys as required. Separate surveys of ecological and cultural resources in the ROW or in the vicinity of the selected route should be performed so that resources may be protected and baseline conditions established in advance of a project.

- Install erosion-control and sediment-control measures as required by permits or project plans prior to starting construction of roads or structures.

- Install permanent and temporary access roads as needed to support construction and operation of the line, but minimize the number and length of such roads and avoid sensitive areas, where possible.

1.9.2 Construction BMPs

The following BMPs affect the manner in which construction activities are carried out and are designed to identify preferred ways of carrying out activities to reduce their impacts:

- Implement blasting controls as required by permits and by project health and safety plans. The timing of blasting should be orchestrated to minimize the number of blasts and duration of blasting over the course of a project and to blast only during daylight work hours, after all safety precautions have been implemented.

- Implement noise controls as required by permits and as specified in work plans. Noise-control measures would involve controls on noise sources, including mufflers and enclosures for machinery, as well as appropriate timing of noisy activities.

- Implement spill controls and cleanup as needed and as specified in permits and work plans. Spill-control and cleanup procedures and materials should be at hand during construction, and workers should be trained in their use.

- Implement hazardous materials containment in accordance with permits and plans. Typically, controlled areas are set up for the handling of hazardous materials that employ primary and secondary containment measures to assure that hazardous materials are not released to soil or water.

- Implement waste and trash management/disposal in accordance with permits and work plans.

- Protect sensitive habitats and species, when encountered, in accordance with work plans and training. Workers should be able to recognize these sensitive resources and follow procedures for protecting them during construction.

- Control invasive species through approved use of pesticides, if necessary, or other means in areas that have been disturbed by construction.

- A number of BMPs apply to the performance of specific construction activities, situations, or conditions, as follows:

  - Stay on designated access roads and within designated construction areas.

  - Minimize gravel placement.

  - Use proper grubbing and clearing procedures.

  - Use approved construction methods.

- Consider weather and seasonal factors.
- Avoid working in wet conditions.
- Work in wetlands in wintertime.
- Avoid periods of wildlife courtship, breeding, or nesting.
- Manage excavation water.
- Employ settling ponds, filtration areas, and buffer zones.
- Manage excavation soil.
- Follow a soil management and grading plan.
- Employ setbacks and buffer zones near streams and surface waters.
- Restrict the use of machinery to minimize soil disturbance.
- Protect slopes.
- Restrict vehicle traffic on steep slopes.
- Implement river crossing protections.
- Minimize sedimentation and shade removal.
- Protect natural drainage patterns.
- Implement wetland protections.
- Implement stream protections.
- Employ run-on and run-off controls for roads and work areas.
- Employ equipment fueling controls.

1.9.3 Postconstruction BMPs

The remaining BMPs are implemented after transmission line construction is nominally complete, and relate to site restoration and line operation and maintenance. Many of these activities would be specified in project permits and work plans.

- Site restoration BMPs:
  - Implement revegetation activities in accordance with permits and work plans.
  - Restore contours disturbed during construction.
  - Replace topsoil in accordance with permits and work plans.
  - Maintain erosion controls in accordance the permits and work plans.
  - Restore stream banks disturbed at line crossings.
  - Remove debris and trash in accordance with permits and work plans.
  - Implement brush control in accordance with permits and work plans.
  - Restore and seed temporary access roads in accordance with permits and work plans.
- Operation and maintenance BMPs:
  - Maintain ROW to protect transmission line conductors and to assure access to structures for maintenance and repair.
  - Cut and control vegetation to prevent interference with conductors and possible fault conditions.
  - Use approved methods and equipment, including approved pesticides and machinery, for ROW and line maintenance.
  - Maintain buffer zones to protect sensitive habitats and water resources.
  - Manage cleared vegetation in accordance with permits and plans.
  - Use herbicides in approved manner for ROW maintenance.
  - Maintain line markers used to increase the visibility of conductors to birds and pilots.
  - Manage birds’ nests on support structures in accordance with wildlife management plans and permits.
  - Conduct species and habitat monitoring programs as required in agreements made with involved regulatory agencies to understand impacts of projects on wildlife over the long term.

2 HIGH-VOLTAGE DIRECT CURRENT TRANSMISSION LINES

2.1 BACKGROUND

Given the same overall transmitted power and practical conductor sizes, low-voltage, high-current transmissions will suffer much greater power losses than high-voltage, low-current transmissions. This holds whether DC or AC is used. Historically, it has been very difficult to efficiently transform DC power to a high-voltage, low-current form, whereas with AC this can be done efficiently with a simple transformer. This was the key to the success of the AC system. Modern transmission grids use AC voltages up to 765 kV. However, technology improvements in the last few decades have allowed reliable generation of high-voltage DC (HVDC), resulting in its reemergence for power transmission systems.

HVDC is also more efficient than high-voltage alternating current (HVAC) in that it uses the insulating strength of the line or cable continuously rather than only during the crest voltage, as with AC. Thus for the same level of insulation, the continuous DC voltage can be at least 1.41 ($\sqrt{2}$) times the RMS AC voltage, with power transfer being increased by the same amount. The increase in DC voltage can be even greater than that, since HVDC systems do not require the same additional margin for overvoltages, which occur at switching. The resistance of conductors is also slightly lower for DC current inasmuch as electric fields associated with power frequency AC current forces the current distribution to favor the outer periphery of a conductor. With DC or very low frequency AC, the current distribution is more uniform, so the electrical resistance is less. These intrinsic characteristics can result in an HVDC conductor transmitting on the order of 60% more power than the same conductor with same insulation in an AC system (Barthold 2004).

Higher voltages reduce the transmission power loss or reduce the cost of conductors when transmitting a given quantity of power, since a smaller current is required. Conductor cost is roughly proportional to the current carried, and conductor loss is roughly proportional to the square of the current, so higher transmission voltages improve the efficiency of transmission.

Low voltage is convenient for customer loads such as lamps and motors. The principal advantage of AC is that it allows the use of transformers to change the voltage at which power is used. No equivalent of the transformer exists for direct current, so the manipulation of DC voltages is considerably more complex. With the development of efficient AC machines, such as the induction motor, AC transmission and utilization became the norm.

DC transmission remains the exception, rather than the rule, in power transmission. There are environments where HVDC is the conventional solution, such as in submarine cables and in interconnecting unsynchronized AC systems, but for the bulk of situations, AC transmission remains dominant.

The ability to transform voltages is an important economic and technical consideration as the lower currents required with high-voltage transmission for a given level power require smaller cables and result in less loss of power in the form of heat. Therefore, with high voltages being optimal for bulk transmission and lower voltages for industrial and domestic utilization, the ability of AC to be effectively transformed in voltage a number of times during transmission led it to become, and remain, the dominant means of electrical power transmission.

2.2 ADVANTAGES OF HVDC OVER HVAC TRANSMISSION

Despite alternating current being the dominant mode for electric power transmission, in a number of applications, the advantages of HVDC makes it the preferred option over AC transmission. Examples include:

- Undersea cables where high capacitance causes additional AC losses (e.g., the 250-km Baltic Cable between Sweden and Germany).
- Endpoint-to-endpoint long-haul bulk power transmission without intermediate taps, for example, in remote areas.
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install.
- Allowing power transmission between unsynchronized AC distribution systems.
- Reducing the profile of wiring and pylons for a given power transmission capacity, as HVDC can carry more power per conductor of a given size.
- Connecting a remote generating plant to the distribution grid; for example, the Nelson River Bipole line in Canada (IEEE 2005).
- Stabilizing a predominantly AC power grid without increasing the maximum prospective short-circuit current.
- Reducing corona losses (due to higher voltage peaks) compared to HVAC transmission lines of similar power.
- Reducing line cost, since HVDC transmission requires fewer conductors; for example, two for a typical bipolar HVDC line compared to three for three-phase HVAC.

HVDC transmission is particularly advantageous in undersea power transmission. Long undersea AC cables have a high capacitance. Consequently, the current required to charge and discharge the capacitance of the cable causes additional power losses when the cable is carrying AC, while this has minimal effect for DC transmission. In addition, AC power is lost to dielectric losses.

In general applications, HVDC can carry more power per conductor than AC, because for a given power rating, the constant voltage in a DC line is lower than the peak voltage in an AC line. This voltage determines the insulation thickness and conductor spacing. This reduces the cost of HVDC transmission lines as compared to AC transmission and allows transmission line corridors to carry a higher power density.

A HVDC transmission line would not produce the same sort of extremely low frequency (ELF) electromagnetic field as would an equivalent AC line. While there has been some concern in the past regarding possible harmful effects of such fields, including the suspicion of increasing leukemia rates, the current scientific consensus does not consider ELF sources and their associated fields to be harmful. Deployment of HVDC equipment would not completely eliminate electric fields, as there would still be DC electric field gradients between the conductors and ground. Such fields are not associated with health effects.

Because HVDC allows power transmission between unsynchronized AC systems, it can help increase system stability. It does so by preventing cascading failures from propagating from one part of a wider power transmission grid to another, while still allowing power to be imported or exported in the event of smaller failures. This feature has encouraged wider use of HVDC technology for its stability benefits alone.

Power flow on an HVDC transmission line is set using the control systems of converter stations. Power flow does not depend on the operating mode of connected power systems. Thus, unlike HVAC ties, HVDC intersystem ties can be of arbitrarily low transfer capacity, eliminating the “weak tie problem,” and lines can be designed on the basis of optimal power flows. Similarly, the difficulties of synchronizing different operational control systems at different power systems are eliminated.

Fast-acting emergency control systems on HVDC transmission lines can further increase the stability and reliability of the power system as a whole. Further, power flow regulation can be used for damping oscillations in power systems or in parallel HVAC lines.

The advantages described above encourage the use of DC links for separating large power systems into several nonsynchronous parts. For example, the rapidly growing Indian power system is being constructed as several regional power systems interconnected with HVDC transmission lines and back-to-back converters with centralized control of these HVDC elements (Koshcheev 2001).

Likewise, in China, ±800-kV HVDC will be the main mode used to transmit large capacity over very long distances from large hydropower and thermal power bases. Other applications involve long-distance transmission projects with few tie-ins of power supplies along the line (Yinbiao 2005).

2.3 DISADVANTAGES OF HVDC TRANSMISSION

The main disadvantages of HVDC transmission systems, including DC links connecting HVAC systems area, are summarized below:

- Converter stations needed to connect to AC power grids are expensive. Converter substations are more complex than HVAC substations, not only in additional converting equipment, but also in more complicated control and regulating systems. Costs of such stations may be offset by lower construction costs of DC transmission lines, but offsets require DC lines of considerable length.

- In contrast to AC systems, designing and operating multi-terminal HVDC systems is complex. Controlling power flow in such systems requires continuous communication between all terminals, as power flow must be actively regulated by the control system instead of by the inherent properties of the transmission line.

- Converter substations generate current and voltage harmonics, while the conversion process is accompanied by reactive power consumption. As a result, it is necessary to install expensive filter-compensation units and reactive power compensation units.

- During short-circuits in the AC power systems close to connected HVDC substations, power faults also occur in the HVDC transmission system for the duration of the short-circuit. Inverter substations are most affected. During short-circuits on the inverter output side, a full HVDC transmission system power fault can be caused. Power faults due to short-circuits on the rectifier input side are usually proportional to the voltage decrease.

- The number of substations within a modern multi-terminal HVDC transmission system can be no larger than six to eight, and large differences in their capacities are not allowed. The larger the number of substations, the smaller may be the differences in their capacities. Thus, it is practically impossible to construct an HVDC transmission system with more than five substations.

- The high-frequency constituents found in direct current transmission systems can cause radio noise in communications lines that are situated near the HVDC transmission line. To prevent this, it is necessary to install expensive “active” filters on HVDC transmission lines.

- Grounding HVDC transmission involves a complex and difficult installation, as it is necessary to construct a reliable and permanent contact to the Earth for proper operation and to eliminate the possible creation of a dangerous “step voltage.”

- The flow of current through the Earth in monopole systems can cause the electro-corrosion of underground metal installations, mainly pipelines.

Some of the above-listed disadvantages can be eliminated with the use of new technologies. In particular, disadvantages such as a complete power fault of the HVDC transmission system during short-circuits in the AC power system and reactive power consumption can be eliminated completely, or mostly, with the use of turn-off thyristors. (Thyristors are discussed in the following section.) Several research centers are working on improving high-capacity turn-off thyristors and also on new types of converter devices for high-capacity HVDC transmission.

Finally, there are several new techniques for the perfection of grounding devices, providing for decreased electro-corrosion impacts and the formation of so-called “metal return,” which precludes the working current from flowing through the ground. Other techniques aimed at perfecting HVDC technology are also being developed (Koshcheev 2001).

2.4 HVDC TECHNOLOGIES

2.4.1 Rectifying and Inverting Components

The conversion of AC current to DC is known as rectification, and from DC to AC as inversion. Early systems used mercury-arc rectifiers, which proved unreliable. The thyristor valve was first used in HVDC systems in the1960s. Modern converters/inverters perform either function. The thyristor is a solid-state semiconductor device similar to the diode but with an extra control terminal that is used to switch the device on at a particular instant during the AC cycle. The insulated-gate bipolar transistor (IGBT) is now also used for rectification and inversion.

Because the voltages in HVDC systems, which are around 500 kV in some cases, exceed the breakdown voltages of the semiconductor devices, HVDC converters are built using large numbers of semiconductors in series.

The low-voltage control circuits used to switch the thyristors on and off need to be isolated from the high voltages present on the transmission lines. This is usually done optically. In a hybrid control system, the low-voltage control electronics send light pulses along optical fibers to the high-side control electronics. A direct light triggering system instead uses light pulses from the control electronics to switch light-triggered thyristors (LTTs). A complete switching element is commonly referred to as a “valve,” irrespective of its construction.

Many converter stations are set up in such a way that they can act as both rectifiers and inverters. At the AC end, a set of transformers, often three separate single-phase transformers, isolate the station from the AC supply, provide a local earth, and provide the correct eventual DC voltage. The output of these transformers is connected to a bridge rectifier of a number of converter valves. The basic configuration uses six valves, connecting each of the three phases to each of the two DC rails. However, with a phase change only every sixty degrees, considerable harmonics (AC signature) remain on the DC rails.

An enhancement of this configuration uses twelve valves (often known as a twelve-pulse system). The AC is split into two separate three-phase supplies before transformation. Twelve valves connect each of the two sets of three phases to the two DC rails, resulting in a thirty degree phase difference between each of the sets of three phases, which considerably reduces harmonics. In addition to the conversion transformers and valve sets, various passive resistive and reactive components help eliminate harmonics on the DC rails.

2.4.2 AC Network Interconnections

Using thyristor technology, only synchronized AC networks can be directly interconnected, those with the same frequency and that are in phase. However, many areas wishing to share power may have unsynchronized networks. For example, the UK and continental Europe operate at 50 Hz, and Japan has 50-Hz and 60-Hz networks. North America, while operating at 60-Hz throughout, is divided into four regions across which power is unsynchronized: East, West, Texas, and Quebec. DC links allow such unsynchronized systems to be interconnected. IGBT-based HVDC systems further add the possibility of controlling AC voltage and reactive power flow.

Power generation systems such as photovoltaic cells generate direct current. Basic wind and water turbines generate alternating current at a frequency that depends on the speed of the driving fluid. In the first instance, high-voltage direct current is generated, which may be used directly for power transmission. The second instance represents an unsynchronized AC system, which may benefit from a DC interconnect. Either situation might benefit from the use of HVDC transmission directly from the generating plant, particularly if plants are located in remote locations.

In general, an HVDC power line interconnects two AC regions of the power grid. Converter stations converting between AC and DC power are expensive, however, and a considerable cost in power transmission. Above a certain break-even distance (about 31 miles for submarine cables and perhaps 375 to 500 miles for overhead cables), the lower cost of the HVDC cable outweighs the cost of the converter electronics. In addition, as noted above, conversion electronics permit managing the power grid by controlling the magnitude and direction of power flow. Thus, HVDC links can increase the stability in the transmission grid.

2.4.3 Polarity and Earth Return

In a DC system, a constant potential difference exists between two rails. In a common configuration, one of the rails is connected to the Earth (earthed), establishing it at Earth potential. The other rail, at a potential high above or below ground, is connected to a transmission line.

The earthed rail at the source end of a DC circuit may or may not be connected to the corresponding rail at the terminal end of the circuit by means of a second transmission line conductor. A monopole transmission line refers to a transmission line without an accompanying earthed conductor.

To complete the circuit, an Earth current (known as a telluric current) flows between the earthed electrodes at the two stations. Such a large Earth current may have undesirable effects in many locations, rendering monopole systems unsuitable. Issues surrounding Earth-return currents include:

- Extended metal objects, such as pipelines, may have a considerable current induced in them, resulting in corrosion unless cathodic protection is employed; sparking and shock problems can occur if earthing is incomplete.

- If either of the earthed electrodes is near the sea, currents could flow through salt water and cause emission of toxic chlorine gas and make the water near the electrode alkaline.

- The presence of a considerable Earth current can generate an extensive DC magnetic field, which could affect navigational compasses.

These effects may be mitigated to some degree by laying a second conductor at ground potential alongside the monopole for carrying the Earth current.

Bipolar transmission offers an alternative to monopolar transmission. In bipolar transmission, a pair of conductors is used, each at a high potential with respect to ground, in opposite polarity. Bipolar transmission is more expensive than monopolar transmission because of the cost of the second line. While monopolar transmission with an Earth return uses two conductors, the Earth return, because it is at Earth potential, requires minimal insulation, reducing cost.

There are a number of advantages to bipolar transmission that can make it an attractive option:

- Under normal load, negligible Earth-current flows occur, minimizing environmental impacts.

- If a fault develops in one line, current can continue to flow using the Earth as a return path, operating in monopolar mode.

- At a given power level, bipolar lines carry only half the current of monopolar lines, as voltage is effectively doubled; thus smaller conductors can be used.

2.4.4 Polarity and Corona Discharge

Corona discharge involves the creation of ions in the air around transmission line conductors by the presence of a strong electromagnetic field. Corona discharge can cause power loss, create audible and radio-frequency interference, generate ozone, and lead to arcing.

While AC coronas are in the form of oscillating particles, coronas from HVDC lines produce a constant “wind” of ions. With monopolar transmission, the choice of polarity of the energized conductor determines the polarity of the ions making up the corona discharge. Negative coronas generate considerably more ozone than positive coronas, and generate it farther downwind of the power line. Thus, the use of a positive voltage reduces the ozone impacts of monopole HVDC power lines. On the other hand, as negative ions are used in home air ionizers and have purported health benefits, particularly in being responsible for condensing particulate matter, the use of negative potential on monopole lines may be considered.

2.4.5 Transmission Lines and Cables

For bulk power transmission over land, overhead transmission lines are most frequently used. These lines most often employ a bipolar configuration using two conductors with opposite polarity.

HVDC cables are also normally used for submarine power transmission. The most common types of cables are the solid and the oil-filled types. Solid cables have insulation that consists of paper tapes impregnated with high-viscosity oil. No length limitation exists for this type, and designs are available today for depths of about 1,100 yards. Oil-filled cable is completely filled with a low-viscosity oil that is maintained under pressure. The maximum practical length for this type of cable is limited to around 37 miles, due to the limitations of oil systems.

Recent developments have produced a new type of HVDC cable, which is available for HVDC underground or submarine power transmissions. This cable is made using extruded polyethylene insulation, and is used in voltage sourced converter (VSC)-based HVDC systems.

2.5 DESIGN, CONSTRUCTION, OPERATION, AND MAINTENANCE CONSIDERATIONS

Construction of HVDC transmission line systems typically takes from 3 years for large, thyristor-based systems, to just 1 year for VSC-based systems, from contract date to commissioning.

Modern HVDC links with microprocessor-based control systems can be operated remotely, and some existing installations in operation are completely unmanned. Since such systems are designed to operate this way, a few skilled people can operate several HVDC links from one central location.

Maintenance of HVDC systems is comparable to that of HVAC systems. The high-voltage equipment in converter stations is comparable to the corresponding equipment in AC substations, and maintenance can be executed in much the same way.

One week per year of normal routine maintenance is recommended. Newer systems may go for 2 years before requiring maintenance. Bipolar systems can continue to operate at near normal levels during maintenance, while one pole continues to operate at elevated load while the other is stopped for maintenance. Preventive maintenance would target up to 98% availability, considering operating disturbances and planned outages (Rudervall et al. 2000).

2.6 HCDV COSTS

Comparing the costs of a thyristor-based HVDC system to an HVAC system, the investment costs for HVDC converter stations are higher than those for HVAC substations, but the costs of transmission lines and land acquisition are lower for HVDC. Furthermore, the operation and maintenance costs are lower in the HVDC case. Initial loss levels are higher in the HVDC system, but they do not vary with distance. In contrast, loss levels increase with distance in a HVAC system.

DC converter station costs and system losses are a relatively high part of total cost, while transmission line costs are relatively low, compared to AC systems. Thus, at some transmission line length, costs are even.

In estimating the breakeven distance, it is important to compare bipolar HVDC transmission to double-circuit HVAC transmission, especially when reliability is considered. Comparing the costs for an HVAC transmission system with those of a 2,000-MW HVDC system indicates that HVDC becomes cheaper at distances greater than about 435 mi. However, since system prices for both HVAC and HVDC have varied widely even for a given level of power transfer, market conditions at the time a project is built could override these numerical comparisons between the costs of an AC versus a DC system.

While technological developments are pushing HVDC system costs downward, and environmental considerations have pushed HVAC costs upward, HVDC and HVAC systems could be considered as equal cost alternatives for the purposes of an early-stage evaluation of transmission system types (Rudervall et al. 2000).

2.7 SYSTEM CONFIGURATIONS

The controllability of current flow through HVDC rectifiers and inverters, their application in connecting unsynchronized networks, and their applications in efficient submarine cables mean that HVDC cables are often used for the exchange of power at national boundaries. Offshore wind farms also require undersea cabling, and their turbines are unsynchronized. In very long distance connections between just two points, for example, around the remote communities of Siberia, Canada, and the Scandinavian North, the decreased line costs of HVDC also make it the usual choice.

A HVDC link in which the two AC-to-DC converters are housed in the same building, with the HVDC transmission existing only within the building itself, is called a back-to-back HVDC link. This is a common configuration for interconnecting two unsynchronized grids. The most common HVDC link configuration is a station-to-station link, in which two inverter/rectifier stations are connected by means of a dedicated HVDC link. This is also a configuration commonly used in connecting unsynchronized grids, in long-haul power transmission, and in undersea cables.

Monopolar systems carry typically 1,500 MW and are most often used in undersea applications. A bipolar link uses two wires, one at a high positive voltage and the other at a high negative voltage. This system has two advantages over a monopolar link. First, it can carry twice as much power as a monopolar link, typically 3,000 MW (the current is the same, but the potential difference between the wires is doubled). Second, it can continue to operate despite a fault in one of the wires or in one module of the converter equipment, by using the Earth as a backup return path. Consequently, the accident rate of bipolar HVDC transmission lines is similar to the accident rate of HVAC double-circuit lines. After shutdown of one pole, spontaneous overloading of the other pole is prevented by emergency control systems.

Modern HVDC transmission lines can be realized with several terminals. These are called multi-terminal HVDC transmission systems. Multi-terminal HVDC power transmission (using three or more stations) is more rare than the other two configurations, due to the high cost of the inverting/rectifying stations. The multiple terminals can be configured in series, parallel, or as a hybrid (a mixture of series and parallel). Parallel configuration tends to be used for large-capacity stations, and series for lower-capacity stations. This is an active area of research.

So far, only a few multi-terminal systems are in operation. For instance, ABB, Inc. has achieved much success in the area using a new technology called Light® technology. While Light technology is currently applied to rather small HVDC transmission systems, its success suggests the growth in multi-terminal HVDC systems. In some cases, such systems may be used in the Northeast Asian region for connecting several power systems; for example, the power systems of Russia, North Korea, and South Korea (Koshcheev 2001).

2.8 HVDC APPLICATIONS

2.8.1 Applications Favoring HVDC Transmission Systems

HVDC technology is superior to the more common AC technology for the transmission of bulk power over long distances or when transmitting between nonsynchronous AC systems. As noted above, HVDC advantages overall include:

- Lower electrical losses.
- Lower transmission line costs (partially offset by converter costs).
- Reduced environmental impact from more compact ROWs.
- No AC electromagnetic field (EMF) issues.
- Direct power delivery and the absence of loop flow.

Specific factors that favor HVDC applications include:

- Simpler requirements for line tower construction in comparison with HVAC transmission lines, and also lower costs per mile of line and per megawatt of transmitted power.
- Significantly lower costs for cables of the same transfer capacity (relative to HVAC lines).
- The possibility of interconnecting power systems with different nominal frequencies (50 and 60 Hz) and systems using various frequency-regulating standards.
- No limits on the transfer capacity of HVDC lines imposed by stability considerations.
- No need for reactive power compensators on long HVDC transmission lines.
- Independent power flows and frequency regulation in AC power systems that are connected via HVDC lines.
- Significantly decreased mutual influence of emergency processes in interconnected power systems when using HVDC power transfer.
- The possibility that power transfer can continue via one pole of a bipolar line even when the second pole trips during an emergency.

In any specific transmission line application, one or several of the advantages listed above may be important in the selection of HVDC transmission. In addition to these factors, the environmental characteristics of power transmission also may be of considerable importance (Koshcheev 2001). Such factors are discussed in the following section.

2.8.2 Renewable Energy Applications

Power generation systems such as photovoltaic cells generate direct current. Simply-engineered wind and water turbines generate alternating current at a frequency that depends on the speed of the driving fluid. The former generation systems provide high-voltage direct current that may be used directly for power transmission. The latter systems are, in effect, unsynchronized AC systems, which suggests the need for a DC interconnect (Lu and Ooi 2003). In each of these situations, use of HVDC transmission direct from the generating plant may be indicated, particularly if inhospitable locations are involved. In general, however, an HVDC power line will interconnect two AC regions of the power grid.

Machinery to convert between AC and DC power is expensive, and a considerable cost of power transmission. Above a certain break-even distance (about 31 miles for submarine cables and perhaps 375 to 500 miles for overhead cables), the lower cost of the HVDC cable outweighs the cost of the electronics. The conversion electronics also present an opportunity to effectively manage the power grid by controlling the magnitude and direction of power flow. An additional advantage of the existence of HVDC links, therefore, is the potential of increased stability in the transmission grid.

There are several plans for large offshore wind farms and a great potential for more, raising the possibility of offshore HVDC networks. However, there are only a limited number of grid connection points available. In this regard, advantages of HVDC networks include:

- Smaller number of cables going ashore, fewer grid connection points required; also less environmental impact at shore, which is particularly important in Germany where much of the coastline is a national park.
- Power quality equipment can be at the connection points rather than at each turbine.
- Better load factors of HVDC lines.
- Higher redundancy.
- Higher flexibility at feed-in points.
- Possible reduction in cost of grid extension onshore.

Cost estimations for a 70-MW, 62-mile HVDC Light project, including the converter stations but not the cable laying, was $30 million, or $6,935 per mile.

Concerns about the corrosion problems and magnetic fields of DC cables can be reduced by laying cables in close proximity in dipolar pairs. Some paper-covered cables can be converted between AC and DC. The same cable can be used for 150-MW AC and can then be used for 600-MW DC, as the insulation can withstand higher DC voltages than AC voltages. This raises the possibility of laying AC cables initially for a smaller wind farm, then if the wind farm were to be extended, the same cable can be used, but for DC transmission (Weatherill 2000).

2.9 ENVIRONMENTAL IMPACTS OF HVDC TRANSMISSION SYSTEMS

The following discussion largely summarizes a paper by L. A. Koshcheev (2003) on the potential environmental impacts of HVDC lines in comparison to HVAC lines. In the paper, Koshcheev points out that an HVDC transmission system provides environmental benefits over conventional AC technology. The land coverage and the associated ROW are less for a DC transmission line. DC transmission lines require two conductors versus three for comparable AC lines. This feature reduces the visual impact and allows greater power to flow over the same ROW, thus maximizing resources. In addition, the EMF effects associated with HVAC transmission lines are not present in HVDC lines.

The possible influences on the environment caused by high-power electricity transmission systems, either AC or DC, include:

- The effects of electric fields.
- The effects of magnetic fields.
- Radio interference.
- Audible noise.
- Ground currents and corrosion effects.
- The use of land for transmission line and substation facilities.
- Visual impacts.

HVDC lines have some characteristics that can be considered as “positives,” while other HVDC characteristics may be “negatives” from an environmental point of view, relative to corresponding characteristics of HVAC lines. Characteristics of HVDC lines have to be taken into account during the process of choosing transmission line routings and while planning a transmission line project. In the following sections, each of the environmental impacts noted above is discussed with reference to the technical features of HVDC transmission systems.

2.9.1 Effects of Electric Fields

The electric field produced by a HVDC transmission line is a combination of the electrostatic field created by the line voltage and the space charge field due to the charge produced by the line’s corona. Investigations of the environmental influence of electric fields around HVDC transmission lines performed in Canada and Russia have shown that the discomfort to humans that is typically felt under HVAC transmission lines is not observed under HVDC lines. This discomfort arises from spark discharges from humans to bushes, grass, and other vegetation. While discharges also occur under the influence of the HVDC transmission line electric fields, these discharges are quite infrequent in contrast to the discharges caused by HVAC transmission line fields, which can amount to 100 discharges per second. Subjectively, the sensation perceived by a human standing under a HVDC overhead line does not usually go beyond the electrostatic stimulation of hair movement on the head. Such results suggest that electrostatic fields below HVDC transmission lines are limited and generally are not hazardous to humans.

A study done in Canada found that large machines with rubber tires (such as combine harvesters, automobiles, and some others) are not electrically charged to dangerous levels when the machines are standing under HVDC overhead lines. The electrical resistance in the tires of these machines, while high (at about 10 megaohms), turns out to be low enough to prevent the accumulation of a dangerous charge (via charge leakage) even when the machine is standing on dry asphalt. In the case of HVAC overhead lines, induced capacitive currents on large machines may reach dangerous levels.

In addition to a static electric field, the space charge around a DC line produces a flux of ions away from the line. Measurements show that in good weather the ion current existing under an HVDC overhead line (corona) can lead to an increase in the concentration of positive ions in the air from normal 10^3–10^4 levels to 10^6–10^7 per cubic inch. During precipitation events, however, this value can rise several times higher. Positive ion concentrations higher than 10^5 per cubic inch are considered detrimental to health due to prolonged exposure of the human respiratory tract.

The level of corona-induced space charge from HVDC lines is variable, as it depends on weather conditions. Thus, the total electric field and ion current flux near a transmission line must be described statistically. Guidelines designed to limit the health impact of electrical fields from transmission lines typically include separate limits on the total electric field of a DC line including space charge, the electrostatic field, and the ion current density.

Local codes and regulations limiting the electrical field impact exert a large influence on the design of overhead line construction, and on the resulting technical and economic performance of the HVDC transmission lines ultimately built.

2.9.2 Effects of Magnetic Fields

The environmental impacts of transmission line magnetic fields on humans have been less studied than the impacts of electrical fields. According to various estimates, the maximum magnetic field strength of an AC power transmission system varies from 10 to 50 μT (micro Tesla) near the line, while exposure levels at residences, for example, are typically less than 1 μT (BPA 1996).

The magnetic fields associated with DC lines produce no perceivable effects. The strength of the magnetic field around HVDC transmission lines is in the same range as that of the Earth’s natural magnetic field. Unlike AC magnetic fields, which continuously vary in strength and polarity with the associated electric current, DC magnetic fields are of relatively constant strength, orientation, and polarity. Since existing limits to magnetic field exposure are typically much higher than the exposure that would be encountered under HVDC transmission lines, there are effectively no guidelines relating to the design of DC lines relating to magnetic fields.

2.9.3 Radio Interference

The radio interference caused by electric power transmission lines is the result of the corona discharge around conductors at positive voltages. As a result, HVDC line radio interference is generated only by positively charged conductors, whereas HVAC interference is generated by all three AC phases.

Weather conditions have opposite effects on induced radio interference for AC and DC lines. AC lines contribute up to a 10 dB (decibel) increase in radio interference under rainy conditions, while DC line radio interference decreases during rain. DC radio interference levels can be limited to acceptable levels by restricting electric field gradients to about 64 kV/inch. Radio interference levels from HVDC lines are typically 6–8 dB lower than those of HVAC lines of similar capacity.

2.9.4 Audible Noise

Audible noise from DC transmission lines is a broadband noise with contributions extending to high frequencies. The noise is most prevalent in fair weather. Noise levels from a DC line will usually decrease during foul weather, unlike the noise levels on AC lines. Audible noise from transmission lines in residential areas is typically restricted to 50 dB during the day or 40 dB at night.

HVDC transmission line operation noise usually is addressed using the same types of measures used for HVAC lines. The main source of audible noise in the HVDC converter stations, the converter transformer, can be surrounded by screens when the noise level is not acceptable.

2.9.5 Ground Currents and Corrosion Effects

Ground currents are associated with monopole operations of HVDC transmission lines. Monopole HVDC systems are used mostly for submarine power transmission systems, except when continuing power transfer is needed in the event of an emergency outage of one pole of an HVDC bipolar system. When power is transferred through only one pole, it is necessary to provide a return circuit for the current.

For underwater cable monopole HVDC transmission systems, current return is performed through the ground. In the case of an overhead bipolar line operating after an emergency outage on one pole, it may or may not be necessary to provide the opportunity for the current to pass though the Earth for the duration of the emergency. On some occasions, a conductor that normally serves as the lightning guard for the line has been used to enable monopole operation of a HVDC overhead transmission line. In the case of designs with two bipolar HVDC lines situated on one set of towers or routed through the same corridor, the overload capacity of the HVDC conductors can be used. Typically, an HVDC overhead transmission line conductor has the effective cross section to carry double its nominal capacity without being in danger of overheating.

When "metallic return," that is, a separate conductor not used to carry power, is used, HVDC power transmission does not produce ground currents or any attendant concerns. When the current return is through the ground, however, the current path between grounding installations of HVDC converter substations lies through the whole thickness of the Earth, while environmental impacts are limited to the moderate area near grounding installations. If, however, there is an available buried conductor, such as a pipeline, current will return through this conductor. This return path presents a danger to buried metal infrastructure through electro-corrosion. The degree of corrosion depends on the quality of electrical insulation and the effectiveness of the means of electrical corrosion control used with the metal infrastructure present, as well as on the amount of current passing through the object.

Overhead HVDC transmission lines are usually bipolar and operate in a monopole mode only in emergencies. However, all DC lines, except those with an additional conductor, produce some ground currents due to unavoidable dissymmetry when operating under a bipolar scheme. Due to differences in current flow between the two poles, a prolonged current passes through the ground. Usually the dissymmetry current is estimated as 1–3% of the nominal current value.

Complex grounding systems for the HVDC substation are required, particularly when a "metallic return" is not available. In the latter case, grounding electrodes are situated at some distance from the substation to preclude corrosion of underground substation components. The grounding installation must be further designed to preclude dangerous step voltages from appearing near grounding electrodes. Electrodes are made from special materials, and special measures are applied to prevent the ground from drying or otherwise losing its properties as a conductor.

Cathodic protection of buried pipelines or other underground metal objects near the grounding installation might be needed to prevent rapid corrosion of this infrastructure.

2.9.6 Land Use Impacts

Perhaps the most important of the environmental effects related to transmission line construction is the conversion of land use for the transmission system. The land requirements per unit of power transfer capacity for HVAC and HVDC substations are practically the same, because the converters occupy comparatively small areas. However, where grounding installations for current return are necessary, additional land area is needed for the installation and the transmission line from the substation to the installation.

The largest amount of land required for either HVDC or HVAC transmission systems is for the overhead transmission line. A HVDC transmission system can be configured in several different ways, requiring different amounts of land area. The configuration chosen depends mainly on the system reliability requirement for the line in terms of the acceptable emergency power drop in the receiving part of a transmission system. Lines may be configured as one bipolar line, two bipolar (quadrapolar) lines with circuits situated on one tower, two bipolar lines in one corridor, or two bipolar lines that are located in different corridors. In each of these cases, the land use per MW of transmitted power is quite different.

The required amount of land for a HVDC transmission system may be estimated using the following example: For a ±500-kV, 2,000-MW bipolar HVDC transmission system with metallic return, the area for a converter substation is about 22 acres, and the area required for the transmission line ROW is 40 acres per mile of line length.

As a rule of thumb, for overhead HVDC and HVAC transmission lines with equal transfer capacity, the area of total land use and ROW needs for an HVDC transmission line is about two-thirds of (1.5 times less than) that for an equivalent HVAC line. This factor can be quite important in the case of long lines in general, or in the case of lines crossing densely populated areas, national parks, or woodlands with valuable trees species.

2.9.7 Visual Impacts

With respect to visual impacts, HVDC overhead transmission lines offer several advantages over HVAC lines of the same capacity. Bipolar HVDC transmission lines have two conductors, and thus are simpler in design than comparable three-phase HVAC lines with three conductors. HVDC lines also require shorter tower heights in comparison with HVAC lines of equal capacity.

Towers for quadrapolar HVDC lines, which are comparable to double-circuit three-phase HVAC lines, can be designed as flat towers or towers with two cross-arms, depending on conditions in the transmission corridor. While there is thus a choice of tower design options depending on requirements for the line, the dimensions of the towers for a quadrapolar line are smaller than those for comparable double-circuit HVAC lines.

If there is a need to bury portions of the line to protect aesthetic values in certain areas, HVDC lines have economic advantages in comparison with HVAC lines, because HVDC cable is cheaper than HVAC cable of the same capacity. In the case of long lengths of buried cable, HVDC cables do not require compensation for the surplus charge capacity of the buried cable, as do HVAC cables. In other cases where lines may need to be buried, such as to avoid obstacles, the simpler HVDC lines offer advantages over HVAC lines. It might be possible, for example, to lay HVDC cable in railroad tunnels crossing mountain ranges where this option might not be compatible with HVAC lines.

2.10 SUMMARY

During HVDC transmission line project planning, most of the same environmental impact characteristics that are considered in planning a HVAC transmission line project should be taken into consideration. These characteristics include impacts from electrical and magnetic fields, radio interference, audio noise, potential accelerated corrosion of buried metal installations due to ground currents, visual impacts, and land use impacts from siting transmission line towers and substations and limitations imposed on land use in transmission line corridors.

HVDC transmission lines have reduced impacts compared to HVAC transmission lines for many environmental impact measures. These advantages may appear as lower costs for mitigating such impacts when installing HVDC lines compared to HVAC lines. If land use is taken as an overall measure of the comparative environmental impacts of HVAC and HVDC transmission lines of the same relative capacity, HVDC line impacts are roughly two-thirds of those of HVAC lines. Thus, a transmission system that incorporates HVDC power transmission will, as a whole, have reduced impacts compared to one that exclusively employs HVAC transmission lines (Koshcheev 2003).

3 BELOWGROUND TRANSMISSION LINES

Installation of conventional underground cables typically involves permitting, working around traffic and other surface activity, trenching, laying cable, bringing in thermal sands, and avoiding other underground utilities, such as gas pipelines and telecommunication cables, because of generated heat or electromagnetic fields (Malozemoff et al. 2002).

Construction of belowground transmission lines could have substantially greater impacts to soils and associated resources than construction of aboveground lines. Belowground construction would require excavation of the entire length of the line, resulting in large areas of disturbance from the excavation and associated activities, such as heavy equipment use and soil storage. Ecological impacts could be increased by the greater soil disturbance, as could impacts to archeological and cultural resources.

Permanent placement of an excavated line could affect sensitive habitats, such as wetlands, if they cannot be avoided. Such areas might have to be drained to protect buried facilities. Groundwater flow could be affected by the presence of an underground trench.

Socioeconomic impacts could be greater for a belowground line due to greater construction costs. Environmental justice concerns might be increased in some areas, such as those resulting from land disturbance, and reduced in others, such as those resulting from burial of the line.

On the other hand, impacts in a number of resource areas would be reduced as compared to aboveground lines. Visual impacts would be greatly diminished, except where aboveground support facilities are located. Land use impacts could be reduced due to the absence of aboveground structures. Bird strikes would be eliminated. ROW clearance and maintenance and all of its attendant impacts would be greatly reduced. Health and safety impacts would be reduced overall due to a reduction in line failures due to accidents or acts of nature. The positive and negative environmental impacts of underground transmission lines are examined in the following sections.

3.1 ENVIRONMENTAL IMPACTS OF BELOWGROUND TRANSMISSION LINES

The following summary of environmental impacts is largely drawn from a report prepared for The Highland Council, Cairngorms National Park Authority and Scottish Natural Heritage (2005) in the U.K. that assesses the use of underground lines in sensitive areas such as Cairngorms National Park in Scotland.

3.1.1 Land Use

Land use would be impacted in several ways by underground transmission lines. Many of the impacts would be distinct from those due to overhead lines. Restrictions would be placed on locating building structures over underground lines to not damage lines, to maintain access to the lines for repair, and to protect building occupants.

Similarly, no trees would be allowed to grow over lines, as roots could damage lines and block access. Thus, in forested areas, a no-tree path would exist over a buried line. Otherwise, recreational land uses would be little impacted. This attribute of buried lines suggests that their primary use in long-range transmission systems would be in visually sensitive areas such as parks.

Little impact would be expected in many types of agricultural areas after restoration of disturbed surfaces. However, irrigation ditches would not be built over lines, while cultivation directly over the lines might be restricted. Lines would be buried deep enough to allow heavy equipment to pass over.

3.1.2 Geology and Soils

Installation of underground lines requires trenching in soils and might require tunneling, rock cutting, or blasting in along some routes. Turns and bends in the path are constrained by the limited flexibility, or minimum bend radius, of underground cables. Costs are higher than for overhead lines, in large part due to costs for excavating and managing soil. Costs for soil management can be 15 to 30 times more than for overhead lines. If suitable, about 50% of soil can typically be used as backfill.

3.1.3 Water Resources

River crossings could have higher impacts from buried lines than from overhead lines. Three types of river crossings have been used: cable bridges, on-river-bed installation, or below-river-bed installation. To minimize impacts, in-river work should be avoided and below-river-bed installation should be used, when feasible. On-bed installation, using river diversion, might be necessary if below-bed installation is not feasible. This option could have high ecological impacts, however. If used, spawning periods should be avoided. This option also introduces concerns about potential pollution from fluid-filled (mineral oil) conductors.

Below-bed installation using directional drilling or thrust boring would have the fewest impacts, but this approach is not always feasible. It also can present high costs and may produce high levels of disturbance near river banks.

Cable bridges would produce the least water quality impacts, but would introduce other impacts, including visual impacts.

Cable trenches, which are lined with sand or similar material for good heat transfer, might affect drainage patterns, and thus impact both surface water and groundwater hydrology. Such impacts might or might not affect water quality.

3.1.4 Ecological Resources

Impacts from transmission line trenching would be similar to those for installing pipelines and could involve soil disturbance, temporary and permanent loss of habitat, and habitat fragmentation in forested areas. To minimize impacts, best management practices would include avoiding breeding/nesting times and using local seeds for revegetation.

Restoring soils above trenches can be difficult due to changes in soil type, drainage changes, and heat from underground cables during operation. Surface temperatures can rise up to 2°C, while subsoil temperatures can rise up to 10°C at 1-yard depths under transient conditions. These conditions can result in soil drying; shifts in vegetation, for example, in favor of grasses; reduced ability of invertebrates to survive winter; favored survival of some reptiles and amphibians; and favored conditions for some invasive species. These impacts are balanced somewhat by lower impacts to birds from bird strikes or the provision of nesting sites to raptors by overhead lines.

3.1.5 Visual Impacts

Reduction of visual impacts relative to overhead lines is a major factor in favor of underground lines. However, as noted above, underground lines are not without some visual impacts. Impacts along the transmission line route would include the absence of trees above the line, possible vegetation changes due to temperature effects, the presence of access and haul roads during and after line construction, and the presence of soil piles during construction.

Construction impacts would include generally greater impacts from soil disturbance and vegetation changes than for overhead lines. A wider area would be impacted during construction, and total removal of vegetation along the route would be required.

In winter, a possible snow-melt path could be present above lines due to heating during operations. Moreover, the buried line could leave a trace in the landscape that is impractical to integrate completely.

Facilities associated with buried cables would introduce other visual impacts. For example, cable joint bay locations providing access for inspection and servicing of buried lines would be present at periodic intervals. Such locations might require access roads in areas of soft soils, but might not in typical soils, including agricultural areas.

Sealing end compounds (SECs) are areas where underground fluid-filled conductors are joined to overhead lines, which use different conductors. SECs provide sealing of the pressurized oil system of buried fluid-filled lines. To meet insulating requirements, a minimum air clearance for the connected overhead line must be maintained. Thus SECs require a sizable area, typically 2,376 square yards (88 yards × 27 yards) for a 400-kV line. The facilities incorporate an overhead line tower to complete the connection.

Reactive compensators are typically required as a result of the increased impedance due to thicker conductors typically used in underground lines for lower resistive heat production. The facilities are typically located every 12.4 miles on a 400-kV line and are colocated at substations, if possible. These facilities are not required for DC lines, which is one reason DC is used in undersea applications.

3.1.6 Cultural Resources

Buried archaeological resources along a buried transmission line route could be impacted by the required excavation for the line. Impacts would be greatest in fertile lowland areas and floodplains. Higher impacts than for overhead lines would accrue due to greater soil disturbance. To minimize impacts, consultations, evaluations, and mitigation should be performed prior to installation of buried lines. Route selection should consider the locations of cultural resources and avoidance of them, if practical.

3.1.7 Air Quality

Construction of buried lines would produce greater impacts to air quality than those of overhead lines due to the amount of excavation required, the attendant use of heavy equipment, increased road use, and the presence of large soil piles.

Operation of buried lines could produce reduced indirect impacts from carbon dioxide emissions from fossil fuel-powered generation plants resulting from reduced line losses in underground cables, which use large cables to reduce heat.

3.1.8 Noise and Traffic

Traffic impacts during construction would be increased relative to overhead lines, as underground lines require up to five times longer to build than overhead lines. Noise impacts during construction would be similarly higher. During operation, however, corona noise would be eliminated, except at substations.

3.1.9 Socioeconomic Impacts

Impacts on tourism and recreation may be less for underground lines than for overhead lines due to reduced visual impacts. TV and radio interference would also be reduced compared to overhead lines. Economic activity resulting from construction of the lines would be greater for underground lines than for overhead lines.

3.1.10 Health and Safety

Construction-related health and safety impacts could be greater for underground lines than for overhead lines due to the greater time and effort involved. Impacts would appear as a greater number of injuries and deaths during construction.

Health and safety impacts during operations could be reduced compared to overhead lines, as hazards to the public from structures would be reduced. For example, air craft collisions and other hazards from overhead lines and towers would be eliminated. Further, shock hazards from ground faults and downed conductors would be greatly reduced, as would induced AC currents in adjacent pipelines and EMFs.

3.2 UNDERGROUND LINE DESIGN FEATURES AS MITIGATION

Design considerations for the transmission line route for underground lines would include most of the same issues as for overhead lines. Impacts associated with the presence of aboveground structures would be reduced and routes selection may be affected accordingly. Such advantages favor the use of underground distribution lines in urban and residential areas. Underground transmission lines should offer similar benefits. Likewise, routes through valuable farmland, residential areas, and visually sensitive areas might be more acceptable if lines are below ground.

ROW design considerations for the specific placement of belowground lines would focus more on soil and geological conditions and groundwater flow compared to that for aboveground lines. Stream and river crossings would be given great consideration, as crossings can be technically difficult and pose relatively high construction impacts. Similarly, crossings of roads, other buried lines and pipelines, and other infrastructure would be more problematic and have potentially higher construction impacts compared to those of overhead lines. ROW design would seek to minimize these difficulties and associated impacts.

Design mitigation factors for the belowground line structures would likely be more limited than those for overhead lines, as the impacts of the lines are less dependent on such factors when the lines are below ground. Belowground line design factors that could mitigate impacts might include the method of excavation used to place lines, the method used to cross streams, and the design of conductors suitable for various crossing methods. Other design factors would include the number and placement of aboveground support facilities, such as substations, or in the case of future superconducting lines, periodic chilling stations. Design factors affecting the life and reliability of the line would mitigate impacts from reexcavating, decommissioning, or replacing the line.

4 HIGH-TEMPERATURE SUPERCONDUCTOR TRANSMISSION LINES

High-temperature superconductors (HTSs) were discovered in the mid-1980s. These materials lose all resistance to electrical conduction at temperatures above the boiling point of liquid nitrogen (LN2). This temperature is significant because liquid nitrogen is a cheap and abundant refrigerant that could make superconducting transmission lines a practical reality. Low-temperature superconductor (LTS) transmission lines operate at lower temperatures that require liquid helium for cooling. Because of the difficulties and expense of handling liquid helium, LTS transmission lines are not currently expected to be practical.

HTS conductors are typically oxides of copper that also contain the elements barium and yttrium and are called yttrium barium copper oxides (YBCO). As these materials are oxides, they are characteristically brittle and cannot be made into practical conductors using just the pure materials. Instead, current efforts rely on coating these materials onto a flexible metal backing that provides the strength needed for long conductors. A number of forms of the superconducting materials and coating methods have been investigated and are briefly summarized below.

Malozemoff et al. (2002) recently reviewed HTS technologies. With respect to wire technology, applications of flexible, long-length HTS wire are currently in active prototyping around the world, and are on the verge of commercialization.

The leading technology for commercial use is a composite wire referred to as “first generation wire.” It consists of a composite of fine filaments of HTS containing the elements bismuth (or lead), strontium, and calcium in a formulation with copper oxide $[(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10}]$, known as “BSCCO-2223,” embedded in a silver matrix. This material has a superconducting transition temperature of 110 K (–163°C), which is easily achieved with LN2 cooling systems. Conductor wires in the form of a tape several millimeters wide and a few tenths of a millimeter thick are being manufactured by several companies.

First-generation BSCCO wire has been called “DC” wire, but can also be used in low-field AC applications such as cables. Hysteretic losses in such wire must be reduced for applications such as transformers.

Average current density has reached 15,100 A/cm at 77 K in “self-field” in a wire of dimensions 4.2 mm by 0.2 mm carrying 128 A in conductors greater than 100 m in length. This performance is generally deemed to be adequate for commercial-scale electrical equipment.

An emerging alternative HTS conductor technology, known as second generation wire, relies on textured $YBa_2Cu_3O_7$ (YBCO), another high-temperature ceramic. In 1999, this was an early-stage technology that had produced only meter-length conductor prototypes. The main advantage of YBCO is magnetic field dependence that is superior to that of BSCCO, which allows higher current densities. Its main disadvantage is a lower superconductivity transition temperature than BSCCO, with diminishing performance above 77 K. This could be a decisive factor for power transmission, depending on achievable cooling. A further advantage of YBCO could be cost, as the conductors do not require large quantities of silver (Malozemoff et al. 1999).

Recent progress has been achieved using vapor-phase application of a mixture of nanoparticles of barium zirconate (BZO) and YBCO applied to a metal backing strip (Kang et al. 2006). The barium zirconate particles arrange uniformly in this matrix and provide "pins" for microscopic electric current vortices produced by magnetic flux lines, which are present in any electrical environment. The produced vortices, if allowed to wander within the conductor, introduce a kind of electrical resistance. Conductors produced in this study were able to carry high-density currents in the presence of applied magnetic fields. Much of current research revolves around introducing such pins into conductors to achieve the conductor performance needed for practical applications. Others working with this material have also reported success in improving current densities through fabrication improvements. MacManus-Driscoll et al. (2004) report a 1.5–5-fold improvement via enhanced pinning.

Malozemoff et al. (2002) reviewed the status of HTS power transmission cables, finding that, of all the opportunities for HTS in power systems, power transmission cables are the most advanced. In 2001, HTS cable prototypes participated in significant precommercial demonstrations in the United States, Europe, and Japan, with several providing power for industrial and residential uses.

HTS conductors are of two basic designs: cold dielectric (CD) and warm dielectric (WD) (Malozemoff et al. 2002; Mikkonen 2002; Stovall et al. 2001). As the names imply, in cold dielectric designs, the dielectric material is housed inside the thermal insulation of the cable along with the superconductor and the cryogenic coolant; in warm dielectric designs, the dielectric is outside the insulator. The dielectric provides electrical insulation for the conductor. Cold dielectrics require a superconducting shield layer.

In either design, current is carried by layers of HTS tapes wound helically around a flexible tube through which pressurized liquid nitrogen is pumped for cooling. The WD design is simpler and requires fewer HTS tapes, but the total current capacity is limited by eddy current losses arising from AC magnetic fields, and significant heat must be dissipated to the environment.

The CD design has double the number of tapes because the concentric shield layer around each phase carries an equal and opposite current, which cancels out long-range fields; this permits higher current capacity and has the additional benefit of reducing electromagnetic forces between the phases.

In environmentally sensitive areas, a major advantage of HTS vs. conventional copper underground cables lies in greatly simplified installation. This advantage derives from two main characteristics of HTS cables: (1) high power density, and (2) low environmental impacts of CD cables.

With respect to the power density advantage, a single HTS cable may carry the equivalent power capacity of six to nine separate copper conductors. With fewer cables to install, a smaller trench is required for an HTS cable, resulting in less surface disturbance.

The high power-density advantage also allows an existing underground pipe or duct to be retrofitted with a superconducting WD cable carrying three to five times the power of the conventional cable it replaces (and potentially up to 10 times for a CD design). Such retrofits can avoid surface disturbance altogether. The recent Pirelli Cables and Systems cable installation at Detroit Edison successfully demonstrates the practicality of such a retrofit installation in a real-world power grid.

Regarding the second advantage, HTS CD cables emit almost no heat or AC magnetic fields into their surroundings, in contrast to conventional cables. This characteristic reduces the required trench size and associated surface disturbance even more than increased power density. The absence of heat output eliminates the necessity to space cables far apart, backfill with thermal sand, or add cooling pipes, as is required for conventional conductors. Furthermore, HTS CD cables avoid overheating or otherwise affecting other neighboring underground utilities. The absence of AC magnetic fields eliminates AC interference in adjacent utilities. Lastly, since they are cooled by liquid nitrogen rather than oil, HTS cables eliminate the potential for soil or water contamination.

In contrast to conventional cables, HTS cables require cryogenic cooling systems, that is, systems that cool conductors to very low temperatures. The principles of cryogenics in the 77 K range are well known, and implementation in power transmission applications is expected to be relatively straightforward.

Cryogenic stations would be placed at the ends of cable installations of up to several kilometers in length, or regular intervals along longer cables. The systems would recirculate liquid nitrogen through the cores of the cables. Expected thermal losses are on the order of 1 cold-watt/m-phase. Thus, thousands of cold watts (kW) per kilometer would be required. However, nitrogen liquefier systems of this capacity are likely to have long-term reliability problems for practical use in utility environments. Similarly, current cryocoolers, such as Gifford–McMahon and Stirling systems, which generally have lower cooling capacity, also suffer from long-term reliability issues.

A promising alternative for low cost and high reliability is the Stirling pulse tube cryocooler, a relatively new technology with no cold moving parts. Kilowatt-level systems are expected to be possible, and active development is under way. It is expected that such systems will play a significant role in HTS cable commercialization (Malozemoff et al. 2002).

At the current rate of technical development, HTS cables have the possibility of becoming fully commercial for a variety of applications in the next few years. Such a development could be a turning point for the introduction of HTS technology in the electric power grid.

Energy losses in a HTS cable include conductor AC losses, heat flow through thermal insulation, induced losses in the shield (only WD), induced losses in thermal insulation (only WD), heat generated by the viscous flow of the cryogen (LN2), pumping losses, and losses in joints and terminations.

Southwire, Inc. has demonstrated an AC cable (30 m, 1,250 A, 12.5 kV, cold dielectric) with a total heat load of approximately 3.6 W/kA-m. For a 1-km, 2-kA cable, Southwire estimates a total heat load of about 15 kW (Mikkonen 2002). A Danish group has estimated the loss values for a 4-km, 450-MVA (megavolt amperes), 132-kV, three-phase single-core WD cable running at 2 kA to be about 14 W/m phase, which is roughly 25% of the losses in a conventional cable system (Mikkonen 2002).

Commercially available HTSs are already being readied for limited applications around the world. Systems being developed in Europe were reviewed by Mikkonen in 2002. At that time, Pirelli Cavi e Sistemi had established an HTS power cable production facility with a capacity estimated at 12 km/year. The facility fabricated a 20-m coaxial 225-kV CD HTS cable in 2000. In 1999, Pirelli Cavi e Sistemi joined Edison SPA and Centro Elettrotecnico Sperimentale Italiano (CESI) in the development of a 132-kV, 3-kA, 30-m prototype HTS system.

In Denmark, in 2002, the first full-scale HTS cable had been demonstrated in a 30-m, 36-kV, 2-kA AC cable in a power utility substation where the cable line supplies electricity to 50,000 households. The WD cables were manufactured by NKT using 19 km of Bi-2223 from Nordic Superconductor Technologies A/S. A conventional cable runs parallel to the HTS cable, both to permit emergency backup and to allow system testing. Another study in Denmark estimated that the energy losses can be reduced approximately by 40% by use of room temperature dielectric design HTS cables connecting to offshore windmill parks.

Also in 2002, an European consortium including Nexans (Germany), Alsthom (France), Laborelec (Belgium), ZFW-Göttingen (Germany), and Tampere University of Technology (Finland) worked toward a 200-m long, 20-kV, 28-kA, three-phase superconducting power link that would be LN2 cooled. Expected total room temperature losses of the link were about one-seventh of the AC losses in a classical three-phase system using conventional conductors. The three-phase busbar system and cross-sectional dimensions were about four times smaller. A 2-m long, 20-kV, 2-kA/5-kA one-phase model had been constructed and tested (Mikkonen 2002).

Siemens of Germany, in the late 1990s, developed a HTS transmission cable of 110-kV and 400-MVA capacity for use in densely populated areas. The liquid nitrogen-cooled, single-phase AC, cold dielectric cable used coaxial conductors made of layers of multifilament tapes containing BSCCO manufactured by Vacuumschmelze. A silver-magnesium alloy sheath provided the necessary mechanical strength for the conductor. Conductor tapes containing 55 filaments with a total length of 18 km were fabricated using an “oxide powder in tube” (OPIT) process (Leghissa et al. 1999; Rieger et al. 1998).

In Japan, prototype conductors 100 m in length have been tested to verify performance for practical use (Honjo et al. 2003). A three-core (conductors), liquid nitrogen-cooled, 66-kV, cold dielectric cable was tested for 2,400 hours over a 1-year period and showed no loss of performance.

Southwire, Inc. and Oak Ridge National Laboratory have successfully constructed a 30-m, liquid nitrogen cooled, cold dielectric HTS that supplies three manufacturing plants at the company’s headquarters in Carrollton, GA (Stovall et al. 2001). As of August 2001, the prototype line had serviced 100% of customer load for 2,164 hours since its start up in January of that year.

American Superconductor has also had success with a BSCCO OPIT conductor (Malozemoff et al. 1999). Regular production wires hundreds of meters in length have been fabricated that meet critical current carrying capacity needs for transmission, a minimum of 10,000 A/cm^2. Prototype wires produced by the company are mechanically robust, with critical tensile stress up to 120 MPa in unreinforced wires and 265 MPa in wire reinforced with a thin layer of stainless steel soldered to both sides (Malozemoff et al. 2002). In addition to prototype conductors, American Superconductor has placed in actual service a number of magnetic storage devices, transformers and magnet systems that use the company’s HTS wire technology.

As of 2002, American Superconductor production capacities were in the range of several 100 km/year; however, the company had plans for an HTS wire manufacturing plant in Devens, MA, capable of producing 10,000 km/year.

A price performance point of $10/kA-m has been identified as a target for HTS to be competitive with conventional copper wire in most major applications, including power transmission (Malozemoff et al. 1999). American Superconductor produced wire for as low as $200/kA-m in 2002 and had targeted a price performance of about $50/kA-m for wire from the Devens factory.

American Superconductor wires use a sheath made of silver to hold HTS filaments. With this technology, the prevailing cost of silver constrains the cost of the conductors more than the cost of the HTS filaments, which can be reduced through economies of scale. At $5.50 per troy oz in 1999, the estimated cost of silver was $7.50/kA-m, or 75% of the total target cost for manufactured HTS cables (Malozemoff et al. 1999).

The mentioned second generation conductor technology using the HTS material YBCO (transition temperature = 90 K), currently being researched around the world, may attain $10/kA-m, as it does not require a silver matrix, a major cost component of first generation wire (Malozemoff et al. 1999).

5 REFERENCES

Barthold, L.O., 2004, *Hybrid AC/DC System for Electric Power Transmission*. Available at http://www.uspatentserver.com/686/6861825.html. Accessed July 11, 2006.

Berger, R.P., 1995, *Fur, Feathers, & Transmission Lines*, Winnipeg, MB, Manitoba Hydro, System Planning and Environment Division.

BLM and USFS (Bureau of Land Management and U.S. Forest Service), 2006, *Surface Operating Standards and Guidelines for Oil and Gas Exploration and Development*, U.S. Department of the Interior and U.S. Department of Agriculture, BLM National Science and Technology Center Branch of Publishing Services.

BPA (Bonneville Power Administration), 1996, *Electrical and Biological Effects of Transmission Lines: A Review*, Portland, Oregon, December.

BPA, 2003, *Schultz-Hanford Area Transmission Line Project Final Environmental Impact Statement*, Bonneville Power Administration, U.S. Department of Energy, Bureau of Land Management, Bureau of Reclamation, Fish and Wildlife Service, U.S. Department of Interior, Department of Army, U.S. Department of Defense.

Burgen, A.R., 1986, *Power Systems Analysis*, Prentice Hall, Inc., Englewood Cliffs, New Jersey.

DOE (U.S. Department of Energy), 2005, *Tucson Electric Power Company Sahuarita-Nogales Transmission Line Final Environmental Impact Statement*, DOE/EIS-0336, Office of Fossil Energy, U.S. Department of Energy, January.

EIA (Energy Information Administration), 2000, *The Changing Structure of the Electric Power Industry 2000: An Update*, Energy Information Administration, U.S. Department of Energy, Washington, D.C.

EIA, 2002, *Upgrading Transmission Capacity for Wholesale Electric Power Trade*, Energy Information Administration, U.S. Department of Energy, Washington, D.C. Available at http://www.eia.doe.gov/cneaf/pubs_html/feat_trans_capacity/w_sale.html. Accessed February 12, 2007.

EPRI (Electric Power Research Institute, Inc.), 1982, *Transmission Line Reference Book*, Electric Power Research Institute, Inc., Palo Alto, California.

FERC (Federal Energy Regulatory Commission), 2004, *Utility Vegetation Management and Bulk Electric Reliability Report from the Federal Energy Regulatory Commission*, Washington, D.C., September 7.

Hayes, B., 2005, *Infrastructure: A Field Guide to the Industrial Landscape*, W.W. Norton & Company, New York, N.Y.

Highland Council, Cairngorms National Park Authority and Scottish Natural Heritage, 2005, *Undergrounding of Extra-High Voltage Transmission Lines*, prepared by Jacobs Babtie, Manchester, U.K., March, 106 pp., published by Jacobs UK Ltd; figures available at http://www.highland.gov.uk/NR/rdonlyres/0BD67F21-8BC3-4C1A-81FC-1F28C1BBDF6E/0/figs.pdf#search=%22Highlands%20Council%20Cairngorms%20undergrounding%22.

Honjo, S., M. Shimodate, Y. Takahashi, T. Masuda, H. Yumura, C. Suzawa, S. Isojima, and H. Suzuki, 2003, "Electric Properties of a 66 kV 3-Core Superconducting Power Cable System," *IEEE Transactions on Applied Superconductivity*, Vol. 13, No. 2, June.

IEEE (Institute of Electrical and Electronics Engineers, Inc.), 2005, *IEEE History Center: Nelson River HVDC Transmission System, 1972*. Available at http://www.ieee.org/web/aboutus/history_center/nelson_river.html. Accessed July 11, 2006.

Incentives Research Inc., 1995, *A Primer on Electric Power Flow for Economists and Utility Planners*, Boston, Massachusetts.

Johnson, P.B., 2004, Prepared direct testimony of Paul B. Johnson on behalf of the American Electric Power System, Securities and Exchange Commission, Washington, D.C.

Kang, S., A. Goyal, J. Li, A.A. Gapud, P.M. Martin, L. Heatherly, J.R. Thompson, D.K. Christen, F.A. List, M. Paranthaman, and D.F. Lee, 2006, "High-Performance High-Tc Superconducting Wires," *Science* 311:1911–1914.

Koshcheev, L.A., 2001, *Basic Principles of Interstate Electrical Power Links Organization in North-East Asia*, presented at the Workshop on Grid Interconnections in Northeast Asia, held in Beijing, May 14. Available at http://www.nautilus.org/archives/energy/grid/papers/koshcheev.PDF. Accessed July 12, 2006.

Koshcheev, L.A., 2003, *Environmental Characteristics of HVDC Overhead Transmission Lines*, St-Petersburg, High Voltage Direct Current Power Transmission Research Institute, prepared for the Third Workshop on Power Grid Interconnection in Northeast Asia, Vladivostok, Russia, September 30–October 3. Available at http://www.nautilus.org/archives/energy/grid/2003Workshop/Koshcheev_paper_final1.pdf. Accessed July 12, 2006.

Leghissa, M., J. Rieger, H.-W. Neumuller, J. Wiezoreck, F. Schmidt, W. Nick, P. van Hasselt, and R. Schroth, 1999, "Development of HTS Power Transmission Cables," *IEEE Transactions on Applied Superconductivity* 9(2):406–411.

Lu, W., and B-T. Ooi, 2003, "Optimal Acquisition and Aggregation of Offshore Wind Power by Multiterminal Voltage-Source HVDC," *IEEE Transactions on Power Delivery*, Vol. 18, No. 1, January.

MacManis-Driscoll, J.L., S.R. Foltyn, Q.X. Jia, H.Wang, A. Serquis, L. Civale, B. Maiorov, M.E. Hawley, M.P. Maley, and D.E. Peterson, 2004, “Strongly Enhanced Current Densities in Superconducting Coated Conductors of $YBa_2Cu_3O_{7-x}$ + $BaZrO_3$,” *Nature Materials* 3:439–443. Available at http://www.nature.com/naturematerials. Accessed July 11, 2006.

Malozemoff, A.P., W. Carter, S. Fleshler, L. Fritzemeier, Q. Li, L. Masur, P. Miles, D. Parker, R. Parrella, E. Podtburg, G.N. Riley Jr., M. Rupich, J. Scudiere, and W. Zhang, 1999, “HTS Wire at Commercial Performance Levels,” *IEEE Transactions on Applied Superconductivity* 9(2):2469–2473.

Malozemoff, A.P., J. Maguire, B. Gamble, and S. Kalsi, 2002, “Power Applications of High-Temperature Superconductors: Status and Perspectives,” *IEEE Transactions on Applied Superconductivity* 12(1):778–781.

Mikkonen, R., 2002, “Highlights of SC Power Applications in Europe,” *IEEE Transactions on Applied Superconductivity* 12(1):782–787.

NCEP (National Commission on Energy Policy), 2006, *Siting Critical Energy Infrastructure: An Overview of Needs and Challenges*, National Commission on Energy Policy, Washington, D.C.

NewswireToday, 2006, “North American Advanced High Voltage Transmission Technology Market – New Technologies Hold the Key,” press release, August 9. Available at http://www.newswiretoday.com/news/7515/. Accessed February 12, 2007.

Office of Fossil Energy, 2005, *Tucson Electric Power Company Sahuarita-Nogales Transmission Line Final Environmental Impact Statement*, U.S. Department of Energy, Washington, D.C.

Rieger, J., M. Leghissa, J. Wiezoreck, H.-P. Kramer, G. Ries, and H.-W. Neumuller, 1998, “Development of a 10 m Long Superconducting Multistrand Conductor for Power Transmission Cables,” *Supercond. Sci. Technol*. 11:902–908.

Rocketry Online, 2000, INFOcentral. Available at http://www.info-central.org/regulatory/orangebook/storage.html. Accessed February 12, 2007.

Rudervall, R., J.P. Charpentier, and S. Raghuveer, 2000, *High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper*, Energy Week 2000, Washington, D.C., March 7–8. Available at http://www.worldbank.org/html/fpd/em/transmission/technology_abb.pdf. Accessed July 12, 2006.

SDGE (San Diego Gas & Electric Company), 2006, Section 7.13 Public Health and Safety/Hazardous Materials, Chapter 7 Inland Valley Link Impacts, Sunrise Powerlink Project, Sunrise Powerlink Application to California Public Utilities Commission, August 4. Available at http://www.sdge.com/sunrisepowerlink/info/PEA/Chapter_7/7_13_safety.pdf#search=%22toxic%20materials%20in%20transmission%20line%20operation%20and%20maintenance%22. Accessed February 12, 2007.

Stovall, J.P., J.A. Demko, P.W. Fisher, M.J. Gouge, J.W. Lue, U.K. Sinha, J.W. Armstrong, R.L. Hughey, D. Lindsay, and J.C. Tolbert, 2001, "Installation and Operation of the Southwire 30-meter High-Temperature Superconducting Power Cable," IEEE *Transactions on Applied Superconductivity* 11(1):2467–2472.

Thrash, F.R., 2003, "Transmission Conductors — A Review of the Design and Selection Criteria." Available at http://www.southwire.com. Accessed September 12, 2006.

Weatherill, J., 2000, *Review of First International Workshop on Feasibility of HVDC Transmission Networks for Offshore Wind Farms*, Stockholm, UMIST 9, March. Available at http://www.owen.eru.rl.ac.uk/documents/stockholm_hvdc_summary.pdf. Accessed July 11, 2006.

Yinbiao, S., 2005, *Current Status and Development of National Grid in China*, keynote speech at the 2005 IEEE/PES Transmission and Distribution Conference and Exhibition: Asia and Pacific. Available at http://conference.epri.ac.cn/t-d2005ap/speech/K1.pdf. Accessed July 11, 2006.

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