EXTRA HIGH VOLTAGE TRANSMISSION LINES

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CHAPTER I

INTRODUCTION

Since the first electric power was generated by Edison in 1882, the demand for this vital commodity has doubled approximately every ten years. This exponential trend in the United States is clearly shown in Fig. 1 (1), in which the total power output is plotted on a logarithmic scale. The dashed straight line corresponds to an annual increase of 6.9 per cent per year, or doubling every ten years.

It should be noted that the population increase in this country is about 1.7 per cent annually, and the increase in Gross National Product is three to four per cent annually. Thus, it is seen that the consumption of electric power increases about twice as fast as the over-all economy of the nation.

This trend has been essentially the same in all countries of the world, even in the less industrialized nations. In the Soviet Union, however, where the industrial output is rising rapidly, electric power consumption now increases at the rate of 11.3 per cent, or doubling every six years (Fig. 2) (14). Similar high rates of growth are evident in many countries of Africa and Asia. There is no indication that this universal trend of increase in electric power consumption will slacken in the future. Thus, all over the world, electric utilities are faced with the necessity of generating, transmitting, and

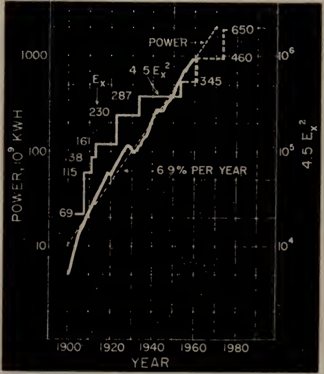


Fig. 1. U.S. power output and quantity $4.5 E_x^2$ (E_x = highest rated system voltage in kv) versus time.

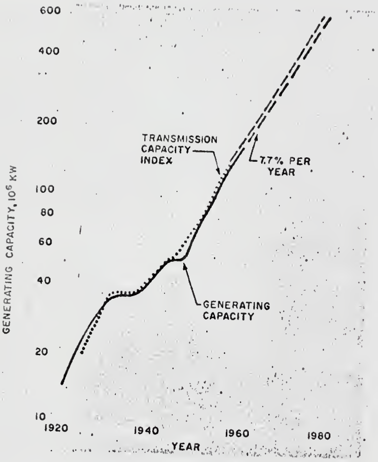


Fig. 2. Generating capacity and the transmission capacity index in the Soviet Union versus time.

distributing twice as much power, six to ten years from now, as they are at present.

Required generation is obtained by building more and more steam-generating plants, which require considerable acreage for their sites and large amounts of cooling water, and therefore cannot always be located close to the load.

Another solution is to tap hitherto undeveloped hydro-electric resources (as is now being done in the Northwest, the West, and in Canada), which are normally several hundred miles from the load centers. New sources of energy are being developed or investigated--for instance, nuclear power, wind power, and tidal power. Again, nuclear plants cannot always be located near the load because of cooling-water requirements and safety regulations of the Atomic Energy Commission.

Once the power is generated, it is then necessary to transmit to the centers of consumption, by means of high-voltage and extra-high-voltage transmission lines, over a distance which will vary according to the amount and type of generation, amount and type of load, and on the inter-connections between adjacent power systems. In order to maintain the transmission capacity in step with the generating capacity and with the load, one possibility would be to double every ten years the number of transmission lines of existing voltages.

This solution is impractical for several reasons. First of all, rights-of-way for power lines are becoming more and more costly and more difficult to obtain. In some cases the right-of-way, say 200 feet wide, may cost more than the extra-high-voltage line built on it; from $50,000 to $100,000 per mile (1). In other cases rights-of-way are not available at all; for instance, near large cities, or in crowded mountain passes. In other cases, the public is not willing to grant easements, maintaining that the transmission lines spoil the landscape, are a safety hazard, cause radio and television interference and lower property values. (Yet the same public continues to demand an uninterrupted flow of electric power at bargain rates!)

Costly and time-consuming litigation ensues, and loss of good will from the public. Even when rights-of-way are available, doubling the number of lines every ten years would mean more than doubling the cost of transmission. This additional cost would be so high that it would be necessary for the power companies to raise their rates frequently. Thus another solution must be found.

The key to this impasse is to gradually increase the transmission voltage in step with the increase of generation and of consumption. The reason is conceptually very simple. The capability, P, of a transmission line is roughly proportional to the square of the voltage used, E, then: $P = K_1E^2$.

Transmission line investment, however, is roughly proportional to the voltage, and so are the operating costs (losses, maintenance, etc.). Consequently, if C is the total annual cost of a line (that is, the initial investment evaluated at a reasonable rate, such as 15 per cent annually, and the operating cost), then:

$$C = K_2E.$$

Consequently, the cost of transmitting an energy unit (kwh) over a unit of distance (mile) is:

$$\frac{C}{P} = \frac{K_2E}{K_1E^2} = K_3\frac{1}{E}$$

or proportional to the inverse of the voltage. Terminal equipment costs increase with voltage and therefore offset some of the advantages of higher voltages discussed above.

As the transmission distance increases, stability considerations become more and more important. In first approximation, the stability limit, P, of a transmission system, consisting of a sending-end hydro station and a receiving-end thermal station, both operating at the same voltage, E, is given by:

$$P = K_4\frac{E^2}{X}$$

where X is the total reactance of the system. This reactance is the sum of the reactances of the two terminal stations (which are independent of transmission distance) and of the line reactance, which is proportional to transmission distance. In order to increase the stability limit, it is necessary either to reduce the reactance (by using more and more lines in parallel, which is expensive and which requires more and more right-of-way), or to increase the voltage.

Right-of-way requirements increase approximately proportional to voltage because of the insulation distances required from the live conductors to the edges of the right-of-way, and between phases. Consequently, if R is the width of the right-of-way, then: $R = K_5E$, and the efficiency of right-of-way utilization (power transmitted per unit-width of right-of-way) is proportional to the transmission voltage; hence:

$$n_R = \frac{P}{R} = \frac{K_1E^2}{K_5E} = K_6E.$$

Summarizing, it can be stated in general terms that: (1) For a constant amount of power to be transmitted, the economic voltage increases with the distance; (2) for a constant distance of transmission, the economic voltage increases with the amount of power to be transmitted; and (3) efficiency of right-of-way utilization is proportional to the voltage.

With these general considerations in mind, we will now discuss the progress of extra-high-voltage (EHV) power transmission in this country and abroad, its present status and future prospects, the problems which must be solved to transmit reliably and economically larger blocks of power over restricted right-of-way, and the progress that is being made in meeting the nation's future requirements for electric power at reduced costs.

CHAPTER II

EARLY AMERICAN DEVELOPMENTS

The inauguration in 1882 of Edison's Pearl Street Station marks the origin of the American electrical utility industry, but this was only a central generating station and a d-c distribution system. The <u>transmission</u> function was lacking in this pioneering development; transmission of a-c power (over several miles) dated from 1886, when a line was built in Italy to transmit 150 hp, over 17 miles, at 2000 volts. The real beginnings of the far-flung American electric system of today were laid in the early California water power developments and in the accompanying requirements for the transmission of electrical power over increasing distances, which necessarily required "high" voltages.

Thus, in 1892, 10 years after Pearl Street, 150 kw of single-phase, hydroelectric power in Southern California was stepped up and transmitted 14 miles, for the first time, at 10,000 volts. A further significant step, made possible in 1895 largely through the experimental and analytical work of early pioneers such as Professor Thomson and Dr. Steinmetz, was the Folsom 3000-kw, 22 miles to Sacramento. Some three years later, this voltage was tripled in a 33-kv, 3-phase line, 81 mile project, also in California.

The next milestone, brought about by further hydro developments, was a 60-kv, 142-mile line from Colgate Hydro to Oakland, first energized at 40 kv in 1901 and raised to 60 kv in 1903 (1). For several years, expansion continued at about this voltage level until the development of the suspension insulator by Hewlett and Buck, patented in 1907, provided a breakthrough to substantially higher levels. The first of these (in 1908) was the 100-kv, 155-mile line from Las Plumas to Oakland. Other projects during the same year included a 100-kv line in Colorado, limited by high altitude to 90-kv operation, and a 110-kv line in Michigan. From this point, developments moved rapidly, first in 1912 to the 140-kv, 125-mile line in Michigan, and in 1913 to the 150-kv, 240-mile line from Big Creek to Los Angeles.

Still under the stimulus of hydro developments, the next major step, one that was to establish a pattern for more than a decade, was the conversion of the 240-mile Big Creek Los Angeles 150-kv line to 220 kv, on May 6, 1923. This line, later increased nominally to 230 kv, was the first to be designated as "extra high" voltage. The 220-230-kv level was introduced in Europe at about the same time and remained the highest in the world for many years until 1936 in the United States, and until 1952 in Europe.

In 1934-35, the Hoover Dam Project, 263 miles from Los Angeles, was developed, utilizing the 237.5-kv transmission level. This voltage remained the highest in the U.S.A. until October, 1953, when American Electric Power put into service its first 330-kv (now 345-kv) line.

CHAPTER III

FOREIGN DEVELOPMENTS

The 287.5-kv level of the Hoover Dam lines remained the highest in the world until 1952, when the first Swedish 400-kv line was energized to transmit power about 600 miles from the generating stations above the Arctic circle to the load centers in the south. The Russian, German, French, and Finnish 400-kv systems were energized in subsequent years; and, at present many European countries have, are building, or are planning to build 400-kv lines, which will all fit into the pattern of a planned European super-grid, which will eventually interconnect all European nations except the Soviet Union.

In order to make this super-grid practical and economical, all European nations had to agree, very early in their planning stage, to standardize the 380-400-kv (420-kv maximum) voltage level. And of more importance they agreed to stick to this level, despite the urge to raise the voltage of existing or future lines, thereby achieving in their country the highest voltage while reducing the transmission costs. The Soviet Union (14, 21) had originally agreed to the 420-kv maximum level, but soon learned that its extra-high voltage lines and stations had been designed with overconservatism. Thus, it was possible to raise the operating voltage first to 420 kv (440-kv maximum), and then to 500 kv (525-kv maximum), with no change in the line design, and relatively minor modifications in apparatus.

Thus, on December 27, 1959, *the Soviet Union achieved the highest transmission voltage in the world*. It has been stated that this conversion from 400 to 500 kv will reduce transmission costs in the order of ten per cent. It is not clear, at present, what type of transmission (a-c or d-c) and what voltage levels will be used for the Soviet Union's future super-grid. Such lines will interconnect all major hydro and thermal stations from the great rivers in Siberia to European Russia's load centers, and will involve distances up to 1500 miles.

At present (1967), many countries, including several of relatively small size (such as Switzerland, Italy, and Czechoslovakia), have built, or are building, lines from 20 to 100 miles long, which are super-imposed over the existing 220-kv system and are also used for international interconnections. Many of these lines are being operated initially at 220 kv and will be transformed later, when economically justified, to 400 kv.

These lines all fit into the planned European super-grid, which is being built, piece by piece, *from the bottom up*, as the need arises, rather than *from the top down* by a supernational power authority, as had been proposed during the power shortages of the postwar reconstruction period. The interesting conclusion is that relatively small countries, corresponding to the size of Eastern states of the U.S.A., are now building 400-kv lines because they are found to be economically justified, and in order to participate in the future benefits of the *super-grid*.

Extra-high-voltage lines are now in operation, or under construction in many other foreign countries, such as Australia (330 kv), Rhodesia (330 kv), Brazil (345 kv), Argentina (380 kv), India (420 kv), and Japan (500 kv).

CHAPTER IV

FUTURE DEVELOPMENTS

After energization, in October, 1953, of the first 330-kv (now 345-kv) line by American Electric Power, extra-high-voltage systems have grown very rapidly in the United States and Canada. Since that time, transmission voltage levels have risen to 500 and 750 kv. Today (11), in North America, work or planning is progressing about 1200 miles of 700-kv transmission, 9000 miles of 500-kv, 6000 miles of new 345-kv, plus about 1500 miles of high-voltage direct current. Preliminary designs for 1000 kv have recently been proposed.

In order to predict future developments of EHV power transmission, it is interesting to study the growth of transmission lines in the U.S.A. since 1926, the earliest year for which statistics are available. Fig. 3 (1) shows total circuit miles, by voltage ranges, and present growth trends. It is seen that the relative number of lines below 90 kv is gradually decreasing, while the relative number of higher-voltage lines, particularly 132 kv and up, is gradually increasing. Fig. 4 (14) shows total circuit miles, by voltage ranges, and present growth for Russia.

Linear extrapolation, for the next 20 years of the total circuit-miles curve, yields approximately 900,000 miles by 1980, but the sum of the extrapolated values of the individual voltage ranges would be approximately 1,000,000 miles. This discrepancy indicates that there must be a continuing gradual shift towards

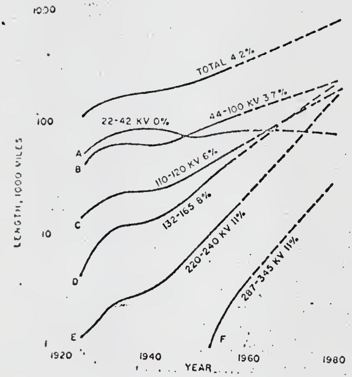


Fig. 3. Length of transmission lines in U.S. versus time, by voltage ranges, and annual-increase trends.

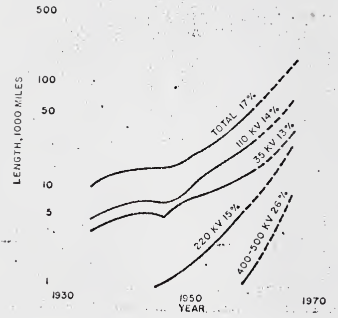


Fig. 4. Length of transmission lines in U.S.S.R. versus time, by voltage class, and annual increase trends.

higher voltages.

Transmission capacity index will be defined as E^2L, where E is the line voltage and L the line length. In the United States this index shows, in Fig. 5 (1), a remarkable correlation with the installed generating capacity. This close parallelism between the two curves indicates that transmission distances have remained constant in the U.S.A., and therefore the need for voltages higher than 220 kv was less urgent than in several European countries, where transmission distances have been increased gradually. Fig. 2 shows the plot of generating capacity and the transmitting capacity for the Soviet Union.

Table 1 (1) gives the surge impedance loading (SIL) of transmission lines for representative voltage levels. If the line is terminated at its characteristic impedence its internal reactive power requirements are completely balanced; consequently no reactive power from external source is required. The line current in this condition is the minimum possible for the given load; consequently the line loss is a minimum. The voltage drop is only ohmic. The power transmitted in this condition is called natural power or surge impedance loading, which is given by

$$P_N = \frac{E_R^2}{Z_o}$$

where E_R is the line voltage and Z_o is surge impedance.

Transmission lines up to 100 miles long can be economically loaded up to twice the surge impedance loading (18). For

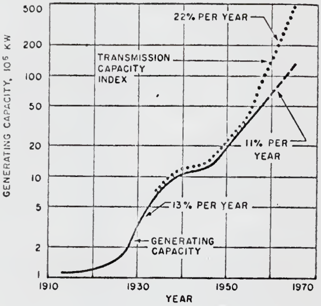


Fig. 5. Generating capacity and the transmission capacity index in the United States versus time.

Table 1. Surge impedance loadings (S.I.L.) per circuit for representative voltage levels.

Kv	S. I. L. (mw)			
	Single conductor	Dual conductors	Triple conductors	Quadruple conductors
115	33	41	---	---
138	48	60	---	---
161	65	81	---	---
230	132	165	---	---
287	206	258	---	---
345	297	372	425	455
400	400	500	570	615
460	530	662	756	815
500	625	780	890	960
690	---	1,480	1,700	1,820
750	---	1,750	2,000	2,150

Note: Surge impedance values assumed are 400, 320, 280, and 260 ohms for single, dual, triple, and quadruple conductors, respectively.

distances over 100 miles, this ratio decreases gradually with increasing length and becomes equal to unity for 300 miles. So for long distances, either the SIL has to be raised (by going to high voltage, see Table 1) or the load has to be distributed on parallel lines.

CHAPTER V

DESIGN CRITERIA, PROBLEMS AND SOLUTIONS OF EHV TRANSMISSION LINES

Introduction

Optimum solution of a given transmission problem may be defined as the solution with the lowest cost which will meet all the specifications and applicable standards, and insure the required reliability. In order to obtain the optimum solution, it is necessary to determine (1) the transmission voltage, (2) conductor configuration and cross section, and (3) insulation levels.

Choice of the voltage depends upon the distance, the power transmitted, the load factor, the economic evaluation factors for I^2R losses, corona losses and reactive power, the annual carrying charges on investment, and, last but not least, the estimated prices of the line and apparatus. Fig. 6 (3) shows the result of a recent study of bulk power transmission, 1500 Mw for 200 miles, at 60 per cent load factor.

It is interesting to note: (1) The decrease in the number of circuits required, from 20 at 138 kv, to 2 at 460 kv. The corresponding decrease in the required width of right-of-way is about five to one; (2) the fact that it is cheaper to transmit coal by wire, at 345 or 460 kv, than coal by rail; and (3) the significant differences between the terminal equipment costs (estimated in 1946) and the costs representative of average 1959 levels.

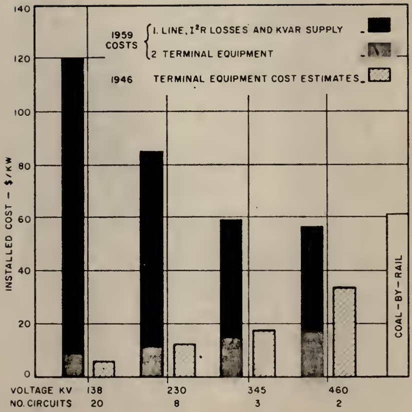


Fig. 6. Cost of transmitting 1500 mw for 200 miles, at 60 per cent load factor, from generator voltage to a 138-kv receiving system.

In 1946, voltages higher than 287 kv appeared to be uneconomical because of the high apparatus costs, whereas today 460-500 kv appears to be the most economical voltage. These advances are due partly to the use of lower basic insulation levels, improved protective devices and practices, greater knowledge about the behavior of insulation, and to larger unit sizes in transformers, with corresponding lower costs per kva.

Looking ahead, present development activity in terminal equipment and circuit design should lead to still further improvement in the economics of transmitting power at extra-high voltages.

Many important factors determine the electrical design and performance of extra-high-voltage lines. These can be classified as follows:

1. Corona loss
2. Economics of conductor configuration and cross-section
3. Radio noise
4. Insulation with regard to lightning, switching surges, and 60-cycle voltages.

The capacity of a transmission line is proportional to its surge impedance loading (SIL) = $\frac{V^2}{Z}$, where V is the voltage and Z the surge impedance of the line. Consequently the current ($I = \frac{V}{Z}$) increases proportionally to the voltage, if single conductors per phase are used, which have a surge impedance value of approximately 400. The cross section of the conductor is proportional to the current, and therefore to the voltage. If R is the conductor radius, then:

$$R \qquad I \quad . \quad V$$

The maximum gradient, G, on the conductor is inversely proportional to the radius, so that:

$$G \qquad \frac{V}{R} \qquad -\frac{V}{V} \qquad V$$

Thus, as the transmission voltage increases, so does the gradient, although with a slower rate. As the maximum possible value for the gradient (in air) is approached, new phenomena appear which affect profoundly the design of EHV lines, stations, and apparatus. These are essentially corona loss and radio noise, which are relatively unimportant (as design criteria) for lines up to 220 kv.

Corona Loss

Corona loss increases nonlinearly as a function of the ratio between the gradient on the conductor surface and the disruptive gradient, determined by Peek's classical formula (17). This ratio increases for constant diameter (with the applied voltage) and for constant surface gradient, with the conductor diameter. For these reasons, as the voltage increases above 220 kv it becomes necessary to use expanded conductors, or two, three, or four conductors in a bundle. Bundle conductors are effective two ways: because the average surface gradient is lower than on equivalent single conductors, and because the disruptive gradient is higher. On the other hand, bundle conductors require a more expansive tower design and present special mechanical problems. Many semi-empirical formulas exist for the determination of fair-weather corona loss. A computer program has been developed by Project EHV (2), using Peterson's formula (19) modified for bundle conductors. For EHV transmission, corona loss may be more than doubled if the conductor is not handled with care; and for a 100-mile, 460-kv line, this difference may be worth approximately $100,000 per year (2). Careful handling of the conductor is equally important in minimizing radio noise.

Much less is known about the calculation of corona loss during bad weather (fog, rain, snow, hoarfrost, and sleet), or even dust storms which occur in the desert. On experimental lines, ratios as high as 100 to 1 (for a-c) have been measured between the highest corona loss and the fair-weather loss. For d-c lines the highest corona loss is about 10 times the fair-weather loss. These results are difficult to extrapolate to actual lines for two reasons: test lines are short, from a few hundred feet to 1.4 miles (Tidd and Leadville); also, test lines do not carry power, and therefore the temperature of the conductor is the same as the ambient temperature.

On Project EHV lines, these drawbacks will be partially eliminated because the line is 4.3 miles long, and there are three complete weather stations, one at each end, and one in the middle of the line. Furthermore, one phase will be heated by circulating current, up to twice the surge impedance loading.

On certain power lines with single conductors, it has been found that during extreme weather conditions, corona loss could absorb up to half the transmitted power. Therefore corona loss can be a real problem. It is generally believed, however, that if bundle conductors are used, corona loss can be controlled and fair-weather losses kept down to less than five per cent of the I^2R losses at surge impedance load.

Even at these low values, the economic significance of corona loss is not negligible, for two reasons. First, load losses are proportional to the square of the current, and the loss factor is about 50 per cent. (Corona losses are always present when the line is energized, so that their loss factor is almost 100 per cent.) Second, as we have seen, foul-weather corona losses may be many times higher than fair-weather losses. It is quite possible that the peak of corona losses is coincident with the system peak load, either in winter (heavy rainstorms, snowstorms, or sleet), or in summer rainstorms.

Consequently, corona loss is evaluated economically by applying an energy charge to the total yearly losses, and a capacity charge to the peak loss. In a computer program, for lack of more precise information, yearly average loss is assumed to be four times the fair-weather loss, and the loss at peak load, twice the yearly average loss. These ratios probably should be higher for single conductors than for bundle conductors.

Assuming the above ratios, the following evaluation may be made (2, 3): (1) For a transmission line from a hydro station (with no storage facilities), the energy charge is assumed to be zero, and the demand charge to be $300X0.15 = \$45$/kw/year. Therefore, the evaluation of the corona losses is $2X45 = \$90$ per kw of average corona loss per year. (2) For a transmission line from a steam station, the energy charge is assumed to be $\$2.50X10^3$ per kwh, and the demand charge to be $\$150X0.15 = \$22.50$/kw/year. Therefore, the evaluation of the corona losses is $2X22.5 + 8760 \times 2.5 \times 10^3 = \$66.90$ per kw of average corona loss per year.

Economics of Conductors

Extra-high-voltage lines for 380-400 kv (420 kv maximum) have been built in Europe with two, three, and four conductors per phase. An interconnection between Italy and Switzerland is being built, partially with single expanded conductors. It does not appear that these differences in line design are justified by system considerations, since loads and distances are often of the same order of magnitude. Similar differences occur for planned 460-500-kv lines in the U.S.A. and Canada. There are also considerable differences in the total cross section per phase, as would be expected.

As is well known, the over-all costs of transmission (capital investment evaluated at an annual rate, say 15 per cent, plus losses and operating expenses) depend upon the conductor cross section, and have a rather flat minimum, which represents the optimum cross section. One curve of this type can be calculated for each of the four configurations, and the four optimum cross sections can be established. Of these, the point with lowest total cost is the optimum optimum, and it represents the best configuration and cross section for the particular case studied.

Since many factors must be included in a thorough economic study, a computer program was developed for this purpose. Results of a typical study (2), involving the transmission of 750 Mw per circuit over 250 miles at 80 per cent load factor, are shown in Fig. 7. Transmission lines with single-expanded, dual, triple and quadruple conductors per phase are considered, all having the same transient and steady-state stability limit. The curves indicate the annual cost of transmitting power (as the differential from an arbitrary cost) versus the total aluminum cross section per phase.

It is clear that, in this particular case, which corresponds to the economic evaluation factors normally used by investor-owned utilities, the optimum solution corresponds to two conductors per phase, 18 inches apart, each having a cross section of about 1500 MCM. The next best solution would be to use three conductors per phase of about 900 MCM each. This would entail an increase in transmission costs of $120,000 per year. Single expanded conductors of 2900 MCM, and four conductors per phase of 650 MCM each, would be considerably more expensive--$300,000 and $220,000 per year, respectively. It may be concluded that appreciable savings can be obtained in

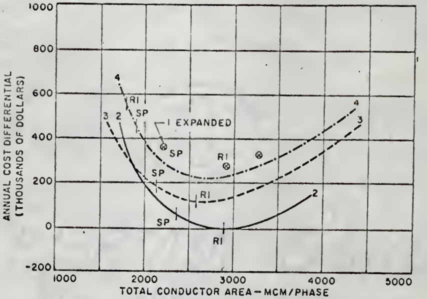


Fig. 7. Annual cost differential versus total conductor cross section per phase, for transmission of 750 mw over 250 miles at 80 per cent load factor.

EHV power transmission by selecting the most economic conductor configuration and cross section.

In certain cases, however, the conductor dimensions are determined by additional factors, which do not have a direct economic value. These factors are sleet prevention and radio noise, and they may require cross sections which are different from the most economic cross section, and therefore they increase the transmission costs.

In Fig. 7, the points marked "SP" correspond to the maximum cross sections which will still prevent sleet formation at surge impedance load, and the points marked "RI" correspond to the minimum cross section which will yield radio interference levels equal to those of the Swedish 400-kv lines, which are regarded as being very satisfactory. It is clear that in all cases, except quadruple conductors, it is not possible to satisfy both of these requirements simultaneously.

To prevent sleet alone, for instance, the cross section of the dual conductors would be reduced from 1500 to 1200 MCM, with a cost increase of about $40,000 per year. For this particular case, the radio noise level of the 1500-MCM conductors is satisfactory. If, however, special requirements would dictate a lower RI level (half of the level of the Swedish lines), it would be necessary to increase the cross section to 1750 MCM, with a cost increase of $40,000 per year.

Keeping constant the total cross section per phase, radio noise may be reduced either by subdividing this cross section into more conductors in the bundle, or by using expanded conductors. Both solutions are more expensive and may be evaluated as indicated above. In any case, this method allows the determination of the cost of RI in line design; and this cost may be compared to the cost of other methods for taking care of possible RI complaints; for instance, by modifying the antennas and receiving apparatus of the customers which are affected.

Radio Noise

Radio and television influence have become important in recent years, as more and more extra-high-voltage lines have been built near populated areas. The public is becoming more conscious of this problem, and more reluctant to grant easements for rights-of-way. The problem is complicated by the great variability of signal levels from the transmitting stations and of the disturbing interference levels, which depend greatly upon the weather, and also by the lack of industry and government standards. In general, a signal-to-noise ratio of at least 30 db (30 to 1 voltage ratio) is required to achieve good reception. Aside from the direct costs in settling complaints or in line design, excessive RI may lead to loss of good will and additional government regulations.

At the lower voltage levels, radio noise is generated mainly by line insulators and hardware in poor condition. Complaints are usually settled by identifying the source and removing the offending element. On extra-high-voltage lines, which are usually well maintained, practically all of the radio noise is generated by the conductor, and therefore can be reduced only by reconductoring the line, a very expensive solution.

Energy distribution of conductor-generated corona pulses has maximum values in the range of 0.15 to 1 megacycle, which overlaps the AM broadcast frequency band and decreases rapidly as the frequency increases beyond this range. Consequently, disturbances to FM broadcasts and television are very low. The few recorded television interference (TVI) complaints are usually due to metal-to-metal discharges, as may occur from unloaded insulator assemblies, where poor contact exists between hardware of successive insulator units.

In 1952-58, Dr. G. E. Adams (3), of Schenectady, developed a rigorous analytical method for calculating the relative RI levels of alternative line designs. This method considers the generation of corona pulses from the conductor, the propagation and attenuation of these pulses along the conductors, and their radiation from the line to the antenna of the receiver.

The mathematical computations are very complex, and therefore are performed on digital computers. Computer in Pittsfield of Project EHV starts from the line design data (voltage, conductor sizes, line geometry, etc.) and ends with a printed profile of the RI level, perpendicular to the conductors (Fig. 8) (3). Since the RI levels are given on logarithmic (db) scale, it is seen that RI decreases quite rapidly with the distance of the antenna from the outermost conductor of the line, in first approximation, as the square (or the 1.5 power) of the distance.

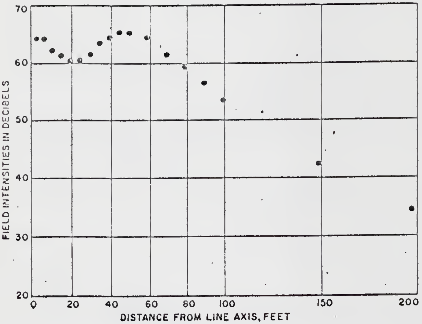


Fig. 8. Radio noise level of an EHV transmission line, versus the distance from the line axis, as plotted by the computer.

Using this approach, the RI level of a new line is predicted by using the known RI level of an operating line as reference. Work is now in progress to establish the calculation of RI on an absolute basis, using the data which is being obtained from measurements on Project EHV and other experimental and operating EHV lines.

Insulation

Insulation design of high-voltage and extra-high-voltage lines has made significant progress in the last 20 years. For instance, the 287-kv Hoover Dam-to-Los Angeles lines were built in 1936, with twenty-four 5-inch insulators, equivalent to about twenty-one 5-3/4-inch insulators. The transformer BIL was 1500 kv (1). At present the same insulation appears suitable for 460 to 500-kv systems. In fact, the Project EHV line is insulated with twenty-two 5-3/4-inch insulators for 460 to 500-kv operation. (The basic impulse insulation level of the General Electric power transformer for the 460-kv line of Pennsylvania Electric, known as Penelec, is 1425 kv.)

Line insulation is determined by three factors: sixty-cycle voltages and over-voltages, switching surges, and lightning. As system conditions vary, and progress is made in these three areas (and in apparatus design), one or the other factor becomes predominant. For instance, when the 345-kv lines of AEP-OVEC and Commonwealth Edison were built, it was believed that lightning would be no problem. English 275-kv lines, and French 400-kv lines (1), have also shown rather poor lightning performance. On other EHV lines lightning is no problem, and thus switching surges are becoming the factor which determines line insulation.

Sixty-cycle operating voltages are normally not the determining factor, except in areas subjected to severe insulation pollution, like the California coast. Sixty-cycle overvoltages, lasting for one or more seconds, may be a problem on long EHV lines during load rejection or overspeeding of generators. For most American conditions, however, the main factors to be considered are lightning and switching surges.

Lightning

To study the effect of lightning on line design and performance, the problem may be subdivided into four successive steps: (1) The natural characteristics (wave shape and amplitude) of lightning are determined as it strikes the line; (2) line response is determined; that is, the voltage across the line insulation (wave shape and amplitude) as a function of the known characteristics of the lightning stroke; (3) dielectric strength of the insulation is determined as a function of the voltage (wave shape and amplitude) applied to it; and (4) since the characteristics of the lightning stroke (length of front and tail, amplitude, frequency, location, etc.) are highly variable, this process is repeated to take into account the statistical distribution of these variables, and the probability of line flashover is finally determined.

Work done in solving these problems will be described in brief. The most difficult problem is, undoubtedly, to determine accurately the characteristic of natural lightning, because of the great variability of this elusive natural phenomenon. Many oscillographic records have been obtained (in the past 30 years) of lightning strokes to tall buildings, tall masts and balloons; many amplitudes of strokes to transmission line towers have been recorded by magnetic links. Unfortunately, this information is not as valuable for transmission line design as was expected. First, because the characteristics of lightning striking very tall objects, such as the Empire State Building, are different from those of lightning striking a 100- to 150-foot tower. Next, most magnetic link measurements were evaluated incorrectly, because the distribution of the magnetic field around the tower legs is not uniform. In any case, magnetic links yield only the amplitude and not the wave shape.

Three new instruments have been developed in Pittsfield for measuring wave shape and amplitude of lightning. These are the teinograph, the linesurge oscillograph, and the shielding-failure indicator.

The teinograph (from the Greek teinein--to stretch, and graphos--to write) records the wave shape of lightning by a delay line and a series of 17 Lichtenberg figures. It has no moving parts, requires no power supply, no photographic film in one version, weighs 20 lb., and is easy to install. It is automatically taken out of service after a stroke has been recorded. Servicing may be done once after every storm period, or at the end of the lightning season. In the latter case, all records after the first one will be lost if an instrument is struck by lightning more than once. Forty teinographs are now installed, or are being installed, on 345-, 220-, and 115-kv lines.

The line-surge oscillograph is a small, rugged, but accurate cathoderay oscillograph, costing approximately one-quarter the cost of ordinary oscillographs. It is turned on automatically whenever there is a storm in the vicinity of the instrument. This type requires a power supply (110 volts alternating current, or batteries), and it must be serviced after six hours of operation. Approximately 70 of these instruments are installed on the Penelec 460-kv line, Project EHV 650-kv line, and on a 220-kv line.

The shielding-failure indicator is a simple, inexpensive device which determines, by means of a Lichtenberg figure, whether lightning hit the ground wires or the phase conductors. Five hundred of these instruments are now installed on 100 miles of the AEP 345-kv lines.

Response of the system to the lightning stroke is determined by tests on a geometrical model of the line. The models usually have a length scale of 1 to 25 or 1 to 50, and represent three towers and two spans. According to model theory, the time scale must be equal to the length scale. Consequently, one microsecond of natural lightning becomes (for the 1 to 50 model) 1/50th of a microsecond, or 20 millimicroseconds. Special techniques had to be developed to measure these extremely short intervals of time, since one millimicrosecond corresponds to the time required by light to travel one foot. Models are easily varied to take into account different conditions; for instance, various ground resistances.

Dielectric strength of insulation is known from tests made in the Pittsfield High Voltage Laboratory. For Project EHV, extensive tests were made on gaps, pedestal insulators and insulator strings, with 18 to 48 suspension insulators.

Internal Voltage, External Voltage and 60-cycle Voltage

It is felt that lightning performance of EHV lines can now be predicted with confidence and that lightning normally will not be the determining factor in establishing the insulation of EHV lines. Therefore, internal overvoltages rather than external overvoltages, are becoming more and more the determining factor for line and station design. Such is the case for Project EHV insulation. Transient analyzer studies are used to determine the magnitude and wave shape of switching surges. Tests made in the Pittsfield High Voltage Laboratory, with surges ranging from 100 X 1000 Ms to 1000 X 3000 Ms, have shown that wet switching - surge strength of long gaps and long insulator strings is of the same order of magnitude as the wet 60-cycle strength. These results are at variance with data obtained at lower voltage, and indicate that, unless switching surges are drastically controlled, it may not be possible to build transmission lines to operate above 1000-kv alternating current.

Vibrations and Use of Dampers

Design loads used on 345-kv lines of the Texas Electric Service Company were based on 1 inch ice and 4-lb. wind at 20F. A close check of existing data indicated that, under these loads, the conductor could be stressed to 53 per cent ultimate. This imposed a 60° initial tension of 25 per cent and a 60° final tension of 20 per cent, both of which were well below the accepted limits being used. After installing a portion of the line at this sag, a high level of vibration was observed in both the conductors and the overhead shield wires. Various tower members had been observed in vibration in addition to the conductor. At this point on all future installations, the tension was reduced in the conductor to 50 per cent of ultimate under maximum design load conditions. This reduced the 60° initial tension to 21.5 per cent and the 60° final tension to 18 per cent of ultimate. The tension in the shield wires was lowered to allow the same increase in sag as had been placed in the conductors. Although the increase in sag of approximately two ft. in a 1000-ft. span required some increased tower height, the reduced level of aeolian vibration well justified the move. It must be noted, however, that even with this reduced tension, there is still a significant amount of vibration present in this line.

However, the vibration was at such a level and continued, due to prevailing wind conditions, for such extended periods of time, that a detailed study was made in October, 1964.

Vibration activity was measured with an accelerometer to determine the frequency of vibration and displacement of the conductor.

These studies indicated that the vibration of the single conductor circuit was substantially greater than that of the bundled circuit although both were well above tolerable limits. The single conductor had vibrations with loop lengths up to 25 ft. and amplitudes ranging up to 1.3 inches, while the loop length in the bundle ranged up to 30 ft. with amplitudes up to 0.8 inch.

Although the conductor did not appear to have been damaged to any appreciable extent, it was decided that, with the severity of the vibration, future damage might occur. Stockbridge dampers were installed on the entire line to provide overall protection to the conductor support, suspension insulators and the towers.

One damper was installed in each span on each shield wire and conductor whether the conductor was installed single or in bundles. These were located on both sides of every second tower in the line for ease of installation.

The dampers appear to have done their job effectively and are included as a standard item for future construction. The alternate solution would be to allow greater sag or shorten the spans in the line. Since every effort is being made to hold down the overall height of the towers in the interest of better lightning protection, the sag now used is to be maintained. From an economic standpoint alone, a 5-ft. extension to the tower would pay over half the cost of the dampers, but the lower overall height is felt to be of considerable importance to the performance of the system.

CHAPTER VI

COMPARISON OF EHVDC AND EHVAC TRANSMISSION

Introduction

In d-c power transmission two conductors, or only one, are required to a circuit. Also, for a given basic insulation level, a d-c circuit can be operated at a higher voltage. Underground and submarine d-c cables are free of such phenomena as dielectric losses and charging current drawn by the cable capacitance.

In addition to these economic advantages, EHVDC offers some unique operating properties that are of particular interest. An EHVDC link is nonsynchronous in nature, eliminating the need for synchronization of the two connected a-c networks. Power transmitted in an EHVDC link can be controlled independently in the link itself, and is not affected by the patterns of generation and consumption in the a-c networks, or by temporary voltage and frequency fluctuations in these networks. Further, an EHVDC link does not add to the short-circuit capacity in the a-c networks; thus, it enables an increase of the power supply in a network, without the corresponding increase in short-circuit level of this network.

A-c line insulation is determined by the switching surges that occur in the system during breaker operation. These surges are up to $2\frac{1}{2}$ times normal rated voltage. Such large surges do not occur on d-c lines. With d-c the determining factor will be the operating voltage, which determines the length of leakage path. Use of insulators of the anti-fog type allows higher operating voltage for a given total length of the insulator string.

Fig. 9a shows the comparison between the tower for a 750-kv, d-c line and for a three-phase 500-kv, a-c line. The power rating is 1000 Mw for the a-c line and 1440 Mw for the d-c line (7).

Another factor of basic importance is that direct current, constant in time, is not subject to inductive effects. The only factor influencing flow of the current is the resistance. D-c ground return current will therefore pass through the well-conducting interior of the earth; this leaves the ground surface unaffected, except in the immediate vicinity of the earth electrode, (see Fig. 9b). Extensive testing and experience, from several operational systems, have proved that it is feasible to use earth return for EHVDC systems. This is not possible with a-c systems.

Practically, the use of earth return requires the selection of a suitable electrode site in the vicinity of each terminal station. There are no technical limits on the distance between the terminal and the electrode site. An electrode line is inexpensive, and can be laid to any convenient site. It is, therefore, generally possible to locate a suitable site and to use earth return.

This factor is of particular significance for cable transmission, especially submarine. Earth return can also be used

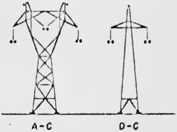


Fig. 9a. Tower for a 750-kv, d-c line and for three-phase, 500-kv, a-c line.

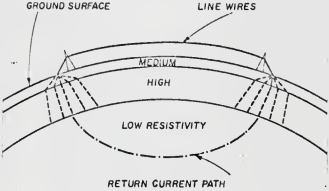


Fig. 9b. D-c ground return current travels through highly conductive earth's interior; not in layer nearest the surface.

with an overhead line. Here, design considerations for the line towers will make it natural to use two conductors, one on each side of the tower. It is normally most suitable to use these conductors as a plus pole and a minus pole, forming a loop for the current. However, with earth return design, each pole can be run as an independent circuit. Also, in case of failure on the one-line pole, the conversion equipment for this pole can be switched to the other pole to work in parallel with equipment already working on this second pole.

A d-c overhead line having a plus pole and a minus pole is, in effect, a double-circuit transmission. Fig. 10a contrasts a double-circuit a-c tower and a d-c tower designed for the same total power. Compared on this basis, d-c allows saving up to 40 per cent in line construction cost (7).

Conversion Equipment

The change from a-c to d-c (and vice versa) is made by electric valves connected to a converter transformer in a three phase, full-wave bridge arrangement called a six-pulse converter. The type of bridge used in HVDC is shown in Fig. 10b. The transformer insulates the d-c system from the a-c system, and at the same time serves the function of providing the desired voltage for conversion.

The factor deciding the output from such a converter is the maximum allowable rating of the electric valves. At present, valves are available for 1800 amp at 150 kv d-c, rated on a six-pulse converter basis. Studies have indicated that the present

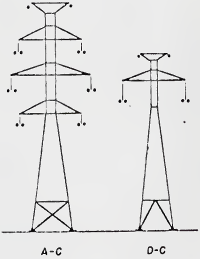


Fig. 10a. Comparison of double-circuit a-c and d-c tower designs.

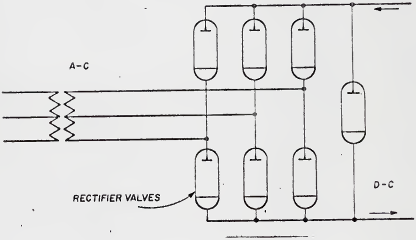


Fig. 10b. Connection diagram of a-c input into valves, which produce direct current.

valve principles may be employed up to ratings of 200-250 kv, through modified design.

Transmission voltage and current for a given transmission is obtained by series and parallel connection of the converters. For example, series connection of three converters per pole, each rated 150 kv, 1800 amp, gives a two-pole (or tower line) rating of 900 kv, 1620 Mw.

Efficiency of the a-c to d-c conversion is very high. The largest losses occur in the transformer; losses in the valves are small. The forward voltage drop in a valve is only 40-50 v. Losses occur also in the damping circuits as well as in filters and auxiliaries. Totally, the losses in conversion are about 1.0-1.5 per cent; or, the efficiency of the conversion is 98.5-99.0 per cent.

The reason for this high efficiency is that no actual conversion of energy from one form to another takes place in a converter. Flow of active power in a three-phase a-c circuit is constant, during a cycle. Only the voltages and current in each individual phase vary. By switching the three a-c phases at the proper instant, power can be made to flow directly over into circuits with direct voltage and current.

Uni-directional action of the valves allows only one direction of direct-current through a converter. Voltage over the converter, however, can be reversed; consequently, the direction of power flow, being a product of voltage and current, can also be reversed. Power can thus be made to flow from the a-c network to the d-c line, and vice-versa. This, of course, is the basis for conversion of power from a-c to d-c (at the sending end), and from d-c to a-c at the receiving end.

It is important to note that the same converter can act as rectifier and as inverter. The mode of operation is decided by the control equipment working on the grids in the valves. Which way the power flows depends on the interaction of the sending-end converter on the receiving-end converter, as directed by the control equipment in the two ends.

In a point-to-point EHVDC transmission, the power flow can thus be reversed by action of the control equipment only, working on the grids in the valves. No mechanical switching of the main circuits is required for this purpose.

For an EHVDC system with one or more taps, this simple method of reversing power flow is not sufficient in all cases. It may be desired to reverse the power flow in one terminal, and leave the direction of power flow in the other terminals unaffected. In such case, the polarity of the transmission is given, and the change of power flow has to be effected through mechanical switching in the main circuit.

The method of switching is based on grid control action; whereby voltage and current in the circuits are brought to zero. The mechanical switching is then performed under no-load conditions. After reversal of connections, the voltage and current are again brought up to the desired value by grid control.

Through the speed and accuracy of the grid control, such a switching sequence can be performed very quickly. The entire procedure described above--from full power flow in one direction to full power flow in the other direction--will take a time interval of about 20-30 cycles.

Operation and Control

In a-c systems, the amount of power transmitted is determined by the difference in phase angles between the a-c networks, or stations connected to the line. Thus, the flow of power is dependent on the pattern of generation (and consumption) and on line characteristics. Power cannot be controlled in the link itself.

An inherent advantage of EHVDC transmission is that both the quantity and direction of power flow may be controlled in the link itself, independent of the associated network. The load dispatcher can set the EHVDC link to transmit power according to a predetermined program; and, the d-c link will continue to transmit power according to this program until ordered to do otherwise by the dispatcher.

This basic advantage derives from the grid control system. By this means, the power-flow through a converter can be controlled with high accuracy and extreme speed. The inherent delay in the grid is a fraction of a cycle. The speed of control of an EHVDC link is limited only by out ability to bring the proper information to the grid control system; and, by the ability of the a-c systems to absorb rapid power changes.

Both rectifier and inverter have current limits. Fig. 11a

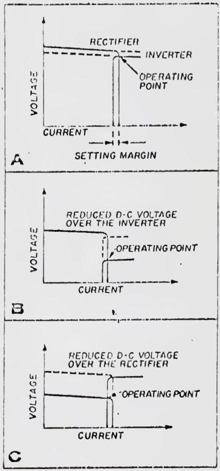


Fig. 11. Relationship between rectifier and inverter. A--current regulation in both units; B--inverter d-c voltage drops due to a fault; C--rectifier d-c voltage drops, due to a fault.

shows the current-voltage characteristics of the rectifier (sending end) and inverter (receiving end).

Control equipment regulates voltage up to the current limit. Once this limit is reached, the controls will function on constant current, and lower the voltage as required to keep the current at its limit value.

As shown by Fig. 11a, the current limit for the inverter is set lower than the current limit of the rectifier. The effect of this is that the inverter will set the voltage of the d-c system, and the rectifier will set the current. A change in the power transmitted over the system is made by changing the current setting of the rectifier. An EHVDC system is thus a constant-voltage system, where power changes are effected by current changes.

Operational Characteristics

The most important characteristic of an EHVDC transmission is that, being a constant-voltage system, the only factor deciding the power is the current in the system. Current is set by the control equipment in the rectifier station, acting on the grids in the mercury-arc valves. This means that it is possible to control the power in the link itself independent of the sending and receiving-end a-c networks.

Temporary fluctuations in frequency and voltage, in the a-c networks in normal operating conditions, will have no effect. A temporary disturbance in one end, be it in frequency, voltage or power, will not be transmitted to the other end. Frequency independence is of particular interest; it means that the frequency of the two systems can very independently of each other. An EHVDC link is non-synchronous in nature. This fact makes it attractive in certain types of transmission systems.

This is of particular interest for an interconnection between large a-c systems. Using a-c in such an interconnection, it is difficult to maintain stability. In an a-c intertie, even under steady-state operation, relatively minor disturbances within either network may lead to interruption of service on the tie. The non-synchronous nature of EHVDC eliminates all necessity for consideration of stability problems, in maintaining continuous operation of the line.

Another interesting characteristic is the behavior of the d-c transmission when there is a major disturbance on either a-c network. Take as an example a short-circuit on the receiving end network, depressing the a-c voltage to 60 per cent. This depression of the a-c voltage will reflect in the inverter voltage which is depressed correspondingly to 60 per cent. The ratio of the two voltages is constant before the tap-changers (on the receiving end converter transformers) can act. Rectifier control equipment will then automatically lower the rectifier voltage correspondingly to keep the set current limit. Referring to the diagram in Fig. 11b, the effect of the fault will only be to lower the operating point along the rectifier current limit. This means that the current fed into the receiving-end network will be only the current set by the control equipment.

Action of the control equipment when faults occur in the sending end is similar. In this case, however, the voltage of the transmission will be set by the rectifier, and the current by the inverter, as illustrated by Fig. 11c. It should be noted that such a change will reduce the current by an amount corresponding to the current margin.

In any case, the current fed into the faulted a-c system will only be the current set by the control system. The d-c transmission thus does not contribute any fault current to the fault in the a-c system. In other words, an EHVDC line connected to an a-c network will not add to the short-circuit capacity of that network.

In practice, this means that the power supply to an a-c system can be increased at constant short-circuit duty of that network. This can be used to postpone breaker replacements that would otherwise be required at increased power levels.

It should be noted that there is a minimum requirement on short-circuit level in the receiving-end network. This is imposed by the regulation of the EHVDC system. The minimum can be expressed as the ratio of short-circuit power to received EHVDC power. As a rule of thumb, this ratio should be 5:1; or higher.

It was stated above that the basic means of control of an EHVDC link is vested in the rectifier current. A control quantity thus has to be transformed into a current value for the rectifier. Any control quantity can, on the other hand, be used. The only thing required is to put the control quantity into a network calculator to obtain a corresponding current value. This makes the control of an EHVDC transmission very flexible, and any desired control program can be obtained. In the first commercial transmission, to Gotland, the link controls the transmitter power, so the frequency in the receiving-end network is kept constant.

It is also possible to build control equipment to provide for a program that effects one type of control under normal operations--for instance, constant power--to be overridden by another type of control during an emergency. With an EHVDC link it is possible to have the link act intelligently, according to a pre-selected program, in case of emergencies.

Limitations of EHVDC Transmission

In d-c there is no easy way of transformation of voltage, as in a-c.

For the operation of an invertor, it is necessary to run it on a leading power factor, thereby requiring the supply of reactive power. This power has to be supplied from the a-c side either by static or synchronous capacitors.

The absence of switching facilities is the greatest limitation of d-c systems. With a-c the current automatically comes to zero every half cycle, and advantage is taken of this in switchgear design. The only problem arising is to prevent restriking.

The d-c system has lower line costs than the corresponding a-c system but needs two converter terminal stations. These cost two to three times more than the corresponding a-c transformer stations and thus basic economic considerations call for a certain minimum transmission distance before d-c can be competitive.

CHAPTER VII

BI-POLAR TRANSMISSION

A basic example of EHVDC system is the bi-polar system, with one converter per pole, as illustrated by Fig. 12a (8). Mostly, such a system is operated with the same current in the plus pole and the minus pole, with the two poles forming a loop for the current. The use of earth return in such a system will provide an attractive possibility for a third conductor, to be used in case of emergencies. If earth return is used, this is a double-circuit system. Each pole is designed as an independent unit, with its control and filtering equipment. In this way, the two poles can be run independently of each other.

For the record, it should be stated that there is no requirement to use earth return. The system can just as well be operated with a high impedance ground. An example of this is the Cross Channel transmission that utilizes system A without ground return.

If the desired system rating is higher than that obtainable with two converters, two or more converters can be used in series in each pole, as illustrated by Fig. 12b. This solution has been selected for the New Zealand transmission. It should be noted that the by-pass valve (and by-pass switch) enables each converter in a pole to be by-passed if a fault occurs in the converter, or if the converter is taken out of service for maintenance. This way, the operation of the transmission can

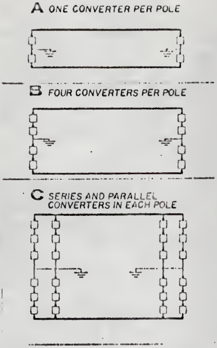


Fig. 12 (A through C). Various arrangements of converters for bipolar EHVDC.

Fig. 12 D. Monopolar system (one conductor, ground return).

continue at three-fourths of rated power during the outage of one converter.

Fig. 12c gives a system solution which can be used in case of very high power requirements. Each branch of the pole equipment has three converters in series, with two branches in parallel in each pole.

Mono-polar (single conductor) transmission is possible with EHVDC with the use of earth return. It provides a system whereby one conductor only is used between the two terminals. The conductor and the ground form a loop for the current, as indicated in Fig. 12d.

This design is particularly attractive for cable transmission, as it makes it possible to use only one cable, thus very large savings on cable cost. This system is used in four of the eight EHVDC transmissions at present in operation, or under construction, namely: Gotland, Sardinia, Konti-Skan and Vancouver (Stage 1-2) (7). This system is, of course, limited to cases where the need is to have an exchange of energy, and where there are no requirements for firm power. In such cases, however, the design offers attractive savings.

CHAPTER VIII

TAPPING EHVDC LINES

In many cases, it is desirable to make one or more taps along the transmission route. The most common system for this is parallel tapping, as illustrated by Fig. 13a, showing a scheme with two taps, or a total of four terminal stations.

It should be mentioned that, technically, it is feasible to make an EHVDC transmission with many taps. Taps at short distances from each other will, however, soon render the EHVDC scheme uneconomical, compared to the EHVAC solution, due to the higher cost of terminals for EHVDC. At present, one or two taps on an EHVDC transmission is the most that will be of practical interest.

The EHVDC technique, however, enables other solutions to tapping at intermediate stations. Fig. 13b illustrates such a solution. As each pole is designed as an independent unit, there is no need to terminate both poles in the same geographical location. On the contrary, they can just as well be located in different places. The connection between the two poles at the two locations can be with the aid of earth, or by a metallic conductor that can then be insulated for low voltage.

Fig. 13c shows a plan that can be used with advantage when the requirement is to tap comparatively small amounts of power. The system is made bi-polar, and the tapping mono-polar. The return current from the tapping will then be through the earth.

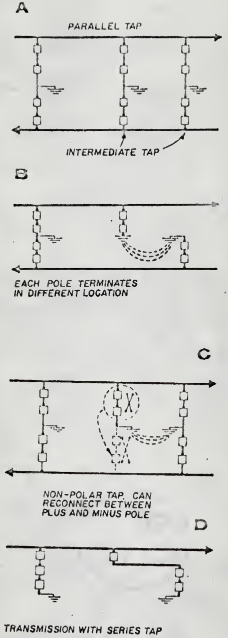

A
PARALLEL TAP
INTERMEDIATE TAP
B
EACH POLE TERMINATES
IN DIFFERENT LOCATION
C
NON-POLAR TAP, CAN
RECONNECT BETWEEN
PLUS AND MINUS POLE
D
TRANSMISSION WITH SERIES TAP

Fig. 13.

Alternatively, it is of course possible to use a low-insulated metallic conductor, should this prove to be advantageous.

In such a solution, with mono-polar tapping, the tapping terminal should be made reversible, so that it can be disconnected in case of a fault on the normal pole and connected to the other pole. This feature will enhance the service reliability of the tap.

Fig. 13d shows another way of making a tap of fairly moderate rating. A converter is connected in series with the transmission at the tapping point. This form is less flexible than the others, as the power to be tapped cannot be regulated freely and independent of the other terminals.

CHAPTER IX

POLE-SWITCHING ARRANGEMENT

In cases where circuit availability is of prime importance, the terminal equipment of one pole can be switched to operate in parallel with that of the other pole. This way, it is possible to switch *all* converters to work on *one* of the conductors in case a fault occurs on the other. This scheme is illustrated in Fig. 14. It should be noted that in such a case, only the converters in *one of the poles* need to be made reversible. It is always possible to switch polarity on the healthy pole.

With this design, the line conductors have to be designed so that they can be operated at *twice rated current*. Generally, this is possible within the thermal limits of the conductor. It should be mentioned that the losses in the line will be *doubled* during such operation.

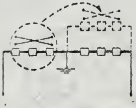


Fig. 14. Reconnection of converter pole equipment in case of fault.

CHAPTER X

PHOTO-STORY OF HYDRO-QUEBEC 735-KV LINE

One of the very interesting points to note is that most of the transmission lines in the world of voltage more than 500 kv are d-c. In Table 2 are summarized principle features and characteristics of EHVDC transmission projects in operation or under construction in which operating voltages range from 500 kv up to 800 kv.

The highest voltage commercial transmission in the world at present is (October, 1967) in Russia. Detailed photographs about the construction and other features of this 800 kv transmission line are not available; however, it will be interesting to see some of the photographs of the second highest voltage commercial transmission in the world, which has been in operation since the Fall of 1965.

The generating station for this transmission line is at Manicouagan and Outardas Rivers, 380 miles northwest of Montreal, Canada; Hydro-Quebec is constructing a generator complex to harness 5500 MW of hydro power (15). To convey the 30 billion kilowatt-hours per year southward to load centers as far away as Montreal, it was decided to build a 735-kv transmission system. The line occupies half of a 535-foot right-of-way that was cleared to accommodate a parallel circuit scheduled to come into partial service in 1966. A total of 18,000 acres of land was cleared. This was just one of the many immense tasks to be

Table 2. Characteristics of long-distance EHVDC line in operation or under construction.

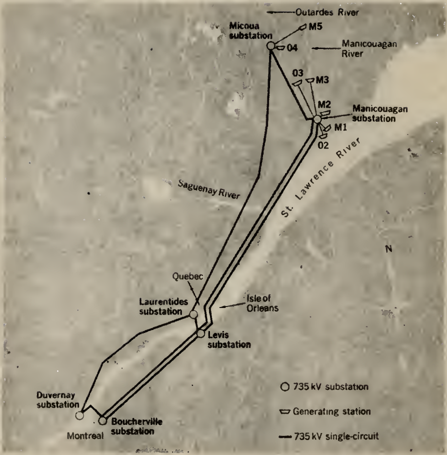
	Pacific Intertie	New Zealand	Volgagrad-Donbass (USSR)	Hydro, Quebec, (Canada)
Voltage,				
Nominal	750 (± 375 kv)	500 (± 250 kv)	--	
Maximum	800 (± 400 kv)	--	800 (± 400 kv)	735 kv
Current,				
Normal Full load	1800 amp	1200 amp	--	--
Emergency	3600 amp	--	--	
Power Transmitted	1400 mw	600 mw	750 mw	5500 mw
Overhead d-c line	853 miles	354 miles (plus 25 miles of submarine cable	295 miles	380 miles
Status	Scheduled for service early in 1969	In service since the fall of 1965	Ungraded by steps and placed in operation at 800 kv during 1965	In service since the fall of 1965

performed in the construction of such an enormous system. (Photo story based on a slide program presented at the IEEE EHV-AC Transmission Conference, Richmond, Virginia, October 4-6, 1965. Material provided by Hydro-Quebec engineers associated with the project.)

EXPLANATION OF PLATE I

Sketch of 380 miles Hydro-Quebec 735-kv transmission line.

PLATE I


Outardes River
Micoua substation
M5
04
Manicouagan River
03
M3
M2
Manicouagan substation
M1
02
St. Lawrence River
Saguenay River
N
Quebec
Laurentides substation
Isle of Orleans
Levis substation
○ 735 kV substation
Generating station
735 kV single-circuit
Duvernay substation
Montreal
Boucherville substation

EXPLANATION OF PLATE II

The Saguenay River crossing was the first of the three crossings scheduled. Because of the height of the mountains on each side, this crossing could be supported directly on the anchor towers. The mountain on the far shore rises nearly vertically to 800 feet above the river. The 5880-foot span is sagged 415 feet with clearance above the water over 300 feet.

PLATE II

EXPLANATION OF PLATE III

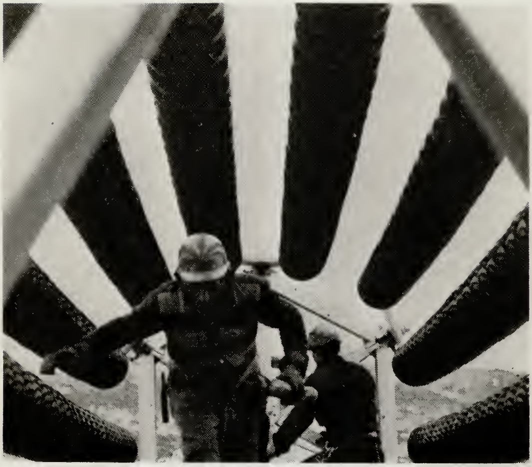
The crossing was over the shipping lanes of the South Channel of the St. Lawrence River at the Isle of Orleans. Shown here is the erection of steel work on this crossing over 500 feet above the river. These towers weigh 710 tons and have ordinary ladders with safety hoops and catwalks with railings for access to obstruction light points and the entire crossarm. Since the St. Lawrence Valley is considered a moderately severe earthquake area, the ability of the crossings to absorb such loading was evaluated.

PLATE III

EXPLANATION OF PLATE IV

Workmen are shown inside the insulator cage of the dead-end assembly for the river crossing conductors. This assembly consists of 12 strings of 33 units, each supported by two primary yokes. Without grading rings, it is 8 feet in diameter by 43 feet in length and weighs 8 tons with a breaking strength of 300 tons. The assembly was raised and installed on the line with temporary steel rods replacing the five tons of insulators.

PLATE IV



EXPLANATION OF PLATE V

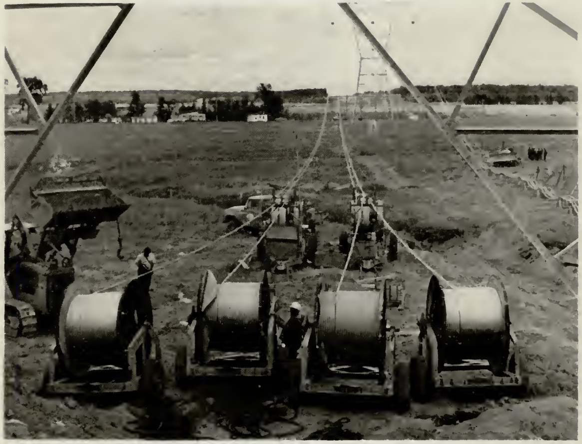
A hydraulically-operated, gasoline-driven cable car is being used on the Saguenay River crossing to remove temporary stockbridge dampers and rubber spacer disks installed during stringing. From the car, the men will then install the permanent X-shaped spacer-dampers to maintain the 18-inch bundle spacing. The car, weighing about one ton, has 16 drive wheels arranged to lift off the conductors in sets and walk over the spacer-dampers after installation.

PLATE V

EXPLANATION OF PLATE VI

Tension stringing kept the conductors off the ground at all times, thereby eliminating scratches, abrasion, and contamination which would cause corona loss when energized. A single 40,000-pound puller with the two 25,000-pound tensioners, shown here, permitted stringing an entire bundle at once. At the right, conductor ends can be seen supported on wood racks ready for splicing. The 1.382-inch diameter ACSR conductors were delivered to the site on 7,000-foot reels.

PLATE VI



EXPLANATION OF PLATE VII

Rough country illustrating the wide spectrum of construction difficulties encountered on such a vast project. In some areas access roads and tote roads had to be carved out of extremely rough terrain.

PLATE VII

CHAPTER XI

CELILO-SYLMAR 800-KV D-C LINE

This 800-kv Celilo-Sylmar d-c line, 853 miles (1372 km) in length, will extend from the Dalles, Oregon to the northern suburbs of Los Angeles. This will represent the highest voltage transmission line in the United States when it is placed in service in 1971 (22). The southern 586 miles (942 km) will be designed and built by the city of Los Angeles and the northern 267 miles (430 km) will be designed and built by BPA (Bonneville Power Administration). The design work which has been done to July, 1967 is described here.

In establishing design criteria, advantage was taken of previous research in Europe and Japan and of experience gained on earlier d-c projects. The design criteria listed in Table 3 are based mainly on tests conducted by BPA since 1963 and described in companion papers (5, 18).

Conductor

The number and design of subconductors were established on the basis of I^2R loss, thermal capacity, and radio interference (RI). Corona losses, though studied, were not a determining factor.

Unlike the case of a long a-c line, there was no incentive to minimize reactance. On the contrary, it is necessary to increase reactance of a d-c line through the addition of large

Table 3. Design criteria--BPA section, Celilo-Sylmar line.

General	
Voltage	
Maximum	800 (± 400)kv
Nominal	750 (± 375)kv
Current	
Normal full load	1800 A
Emergency	3600 A
Maximum power	
Sending end	1400 mw
Receiving end	1350 mw
Length	
BPA section	267 mi (430 km)
LA section	586 mi (942 km)
Total	853 mi (1372 km)
Isokeraunic level	10-30
Design transient OV	1.7 per unit
Towers	
Material	
Dead end	Steel
Guyed suspension	Aluminum
Self-supporting suspension	Steel
Average height	
To crossarm	91 ft-4in (27.8 m)
To ground wire	113 ft-0 in (34.5 m)
Span length	
Ruling span	1150 ft (351 m)
Maximum	4400 ft (1344 m)
Minimum conductor clearance	
To support	93 in (2360 mm)
Above ground	35 ft (10.7 m)
Guy wires	Single 1 in EHS
Pole spacing	
Guyed section	38 ft (11.6 m)
Self-supporting section	41 ft (12.5 m)
At dead ends	45 ft (13.7 m)

Table 3 (concl.).

Suspension insulators	
Maximum string length permitted by tower design	
Insulated units only	148 in (3750 mm)
With hardware	178 in (4520 mm)
Size and shape	6 1/2 by 12 5/8 in
Type	Ball and socket
Mechanical and electrical strength	40,000 lbs (18,120 kg)
Configuration	Free swinging
Number in string	20
String leak distance	400 in (1016 mm)
Strain insulators	
Size and shape	7 3/4 by 12 5/8 in
Type	Ball and socket
Mechanical and electrical strength	66,000 lbs (30,000 kg)
Number in string	24
Conductor	
Type	ACSR
Diameter	1,802 in (45.7 mm)
Size	2300 kcmil (1.808 in^2 = 1165 mm^2)
Stranding	
Aluminum	76 at 0.1790 in (4.53 mm)
Steel	19 at 0.0830 in (2.11 mm)
Conductors per pole	2
Bundle supporting space	18 in (457 mm)
Ultimate strength	
Initial	58,255 lbs (26,400 kg)
Final*	56,200 lbs (25,450 kg)
Tension	
Maximum design	21,000 lbs (9520 kg)
At 60°F (17.8°C)	11,552 lbs (5240 kg)
At 138°F (58°C)	10,024 lbs (4650 kg)
Grounding	
Maximum footing resistance	20 ohms
Overhead ground wire	
Number and material	1/2-in galvanized steel strand

*Strength after occasional loadings to 3600 amperes not to exceed a few hours for an accumulated total time of 1000 hours.

series smoothing reactors at each terminal.

For a single conductor, it would have been necessary to use a larger total cross section to meet the thermal requirements, resulting in a diameter of about 2.8 inches (71 mm). While this did not quite eliminate the single conductor cost advantage, it narrowed it considerably. Reluctance of construction and maintenance forces to handle the very large single conductor finally tipped the scales in favor of the duplex bundle. Once this decision was made, various conductor designs were studied, and a 1.802-inch (45.7 mm) diameter ACSR conductor was found to give the lowest annual cost, including evaluated I^2R losses.

With regard to radio interference, the conductor selected, though slightly smaller than the bundle conductor actually tested (1.802 inches compared to 1.82 inches), should give RI levels well within limits found acceptable for a-c lines. The following favorable factors are also significant:

1. RI from d-c lines decreases during foul weather (5,13).
2. The line is remote from habitations (13).
3. Higher signal-to-noise ratios are acceptable for d-c lines.

There have been some indications that RI levels near d-c lines (and perhaps to a lesser extent near a-c lines) are somewhat higher during high wind, although no very definite correlation has been established (5). Since RI levels seem to be affected very little by high wind velocity when the positive conductor is upwind, it is planned to connect the Celilo-Sylmar Line to provide this condition for the most usual direction of power flow (southward), and for the most frequent wind direction (from the west). However, no particular problem is anticipated when the wind or power flow direction changes.

While tests show clearly that RI from duplex bundle conductor is less than from a single conductor of the same total cross section, it is likely that the RI levels from single conductor would have been acceptable. Single conductor should therefore be considered for future lines in this general voltage class, which do not have the same severe overload requirements.

Clearances

For d-c as for a-c lines, clearances must be designed to achieve an acceptably low probability of flashover when subjected to transient internal overvoltages. Switching surge test data developed for a-c studies appear applicable to the d-c case. The rise time and length of transient surges for d-c lines are apparently comparable to those for a-c lines; however, the d-c over voltage factors are much lower. A study, using a rough simulation of the Pacific Intertie, gave an overvoltage factor of only 1.5 per unit. A more precise study is under way at this writing. Meanwhile, a conservative figure of 1.7 per unit has been used in designing the line, giving a design peak value of 680 kv (22).

In establishing d-c electrical clearances, two approaches were possible, and both were used in this case. The first is a fundamental engineering approach, using the best knowledge available, including much that has accumulated since the formulation of the code. The second is a legalistic approach which seeks the most logical extension of the basic NESC philosophy to a d-c application not foreseen when that code was developed.

Using the first approach, a clearance might be sought to provide a 99.9 per cent (5) probability of withstand for the assumed 680-kv surge, making reasonable allowance for any adverse environmental effects. Based on curve 4 (Fig. 8, of Hill and Kinyon (16)), and assuming a standard deviation of 5 per cent, a required clearance is established between live parts and supports of 70 inches under standard environmental conditions. Allowing 15 per cent additional for adverse temperature, humidity, and air density, a clearance of 80.5 inches (2045 mm) is arrived at.

Second approach suggested, and initially accepted by the Pacific Intertie agencies concerned, is to use a clearance such as the NESC would require for an a-c line having a nominal 60-cycle crest voltage to ground the same as the nominal voltage to ground of the d-c line. Under this interpretation, NESC Rule 235-A3 would here require

$$3 \text{ inches} + (0.2 \text{ inch}) \frac{3\ (375)}{2} - 8.7 = 93 \text{ inches } (2360 \text{ mm}).$$

Clearances were established for the actual tower designs which meet this value.

Further consideration, however, raises serious questions as to the logic of deriving d-c air clearance from a-c air clearance on the basis of normal operating voltages, since it is only the transient overvoltages which are in danger of breaking down the gap. While the NESC does not tie in its clearance formulas with transient voltage factors, it may be noted that its formula for clearance to supports (3 inches for any rms line-to-line voltage up to 8.7 kv, plus 0.2 inch for each kv of excess above 8.7) yields essentially the same result as a BPA formula which was among the proposals considered by the committee which developed the code. The BPA formula is simply 0.2 inch per kv of line-to-line voltage. Its derivation is documented and was based on a ratio of maximum operating voltage to nominal voltage of 1.05, and a transient overvoltage factor of 2.5 per unit. It included allowances for nonstandard atmosphere, including effects of altitude up to 3000 feet. It seems reasonable to suppose that the NESC formula is compatible with these assumptions, since it and the BPA formula give results differing only by one inch.

On this basis, the nominal a-c line-to-line voltage to produce a transient overvoltage of 680 kv, similar to that of the d-c line, is:

$$\frac{680 \times 3}{(2.5) \times (1.05) \times (2)} = 317 \text{ kv}$$

Applying NESC Rule 235-A3, the required clearance from conductor to support is:

3 inches + (0.2 inch) (317 - 8.7) = 64.7 inches (1640 mm).

If 10 per cent is added to allow for the high altitude over much of the line the result is

(64.7)(1.1) = 71.17 inches =, say 72 inches (1825 mm).

While an argument could evidently be made for reducing clearance below the 93 inches established in the present design, it has been decided not to do so on this first line. This may be considered in the case of future lines when more knowledge has been accumulated. No definite design decision has been made concerning the towers to be used at this writing.

Insulators

As in alternating current, the insulators must also provide an acceptably high withstand probability for the design value of maximum internal overvoltage, or 680 kv. Switching surge test data (4) indicate a 99.9 per cent withstand probability for such a surge with a string of only 15 standard 5 3/4 by 10 inches (146 by 250 mm) insulator units. Using 17 units to allow for the possibility of two damaged ones results in a string length, less hardware, of 97 3/4 inches (2490 mm). This assumes normal atmospheric conditions. When allowance is made for nonstandard air density and humidity, and for difference in switching surge withstand characteristics of the high-strength, high leakage insulator designs which will probably be used, the string length needed to withstand switching surges is probably more nearly in the order of 120 inches (3040 mm).

The insulators to be used are 6 1/2- by 12 5/8-inch tempered glass units having a leakage distance of 20 inches. It was decided to use 20 units per string, giving a string length without hardware of 130 inches, and a total leakage distance of 400 inches.

Overhead Ground Wire

BPA does not normally use overhead ground wires on its a-c lines, except near substations for protection of terminal equipment. This is because the isokeraunic level is low in most parts of the region and moderate in the rest, and because fast automatic reclosing has proved very successful. In the Pacific Southwest, however, the use of overhead ground wire has been customary. For the Pacific Intertie a-c lines, because of the great length, consequent great exposure, and their importance, BPA and the other agencies involved have agreed to use overhead ground wires over the entire length.

For the d-c lines, it has been suggested that such protection is less necessary, since power follow current is much less, faults can be cleared, and reclosure accomplished readily and quickly by valve blocking and deblocking. Moreover, a fault will normally involve only half the line capacity. On the other hand, the great length of the line results in an exposure many times greater than for the average transmission circuit. This, plus the desire to be conservative on this first American high-voltage d-c line, led to a decision to provide overhead ground wire protection. BPA will use a single wire, mounted to provide a shielding angle of 30 degrees.

CHAPTER XII

CONCLUSION

The present state of EHV a-c transmission art has been reached only after many decades of study, testing, and operating experience involving much trial and error. The aim here has been to proceed more swiftly to an optimized d-c design, by making full use of all applicable knowledge gained from a-c transmission. It is seen that d-c transmission has its main application where the distances are large and power has to be transmitted in bulk from one place to another without intermediate taps. One of its many advantages is that it is non-synchronous in nature, eliminating the need for synchronization of the two connected a-c networks. One of the principle applications for a-c transmission would be in connection with the relative ease of changing voltage levels by use of transformers.

Extra high voltage a-c and d-c transmission each have their own scope and fields of developments, and there is no competition between a-c and d-c. In fact both are complementary, and will have to be developed to take their own places in order to obtain the best advantages from available natural resources.

REFERENCES

1. Abetti, P. A. and S. B. Crary.
   Progress in Extra-high-voltage Power Transmission, AIEE Transactions, vol. 78, pt. III, June, 1959, pp. 357-71.

2. Abetti, P. A., C. B. Lindh, and H. O. Simmons, Jr.
   Economics of Single and Bundle Conductors for Extra-high-voltage Transmission, AIEE Transactions, vol. 79, pt. III, June, 1960, pp. 138-53.

3. Adams, G. E.
   Radio Interference from High-voltage Lines as Influenced by the Line Design, AIEE Transactions, vol. 77, pt. III, April, 1958, pp. 54-63.

4. Alexander, D. E. and E. W. Boehne.
   Switching-surge Insulation Levels of Porcelain Insulator Strings, IEEE Transaction on Power Apparatus and Systems, vol. PAS-83, November, 1964, pp. 1145-1157.

5. Bailey, B. M.
   Progress Report on BPA HV-DC Test Line-Radio Noise and Corona Loss, presented at the 1966 IEEE Summer Power Meeting.

6. Bellaschi, P. L.
   Recent Developments in High Voltage DC Transmission, Transmission and Distribution, August, 1967.

7. Berglund, O., P. G. Engstrom, and U. Lamm.
   High-voltage D-c and the Planning Engineer, Part I, Power Engineering, December, 1966, p. 46.

8. Berglund, O., P. G. Engstrom, and U. Lamm.
   High-voltage D-C and the Planning Engineer, Part II, Power Engineering, January, 1967, pp. 49-51.

9. Brever, G. D., H. O. Simmons, Jr., and C. A. Woodrow.
   Important Technical and Economic Aspects of High-voltage Transmission, Proceedings of the American Power Conference, (Chicago, Illinois), vol. 22, pp. 533-47, 1960.

10. Carroll, Joseph S. and M. M. Rockwell.
    Empirical Method of Calculating Corona Loss from High-voltage Transmission Lines, AIEE Transactions, May, 1937, p. 558.

11. Dillard, J. K.
    Status Report on EHV Transmission Design, IEEE Transactions on Power Apparatus and Systems, June, 1966.

12. Fuller, W. F.
EHV Line Design, Transmission and Distribution, January, 1967.

13. Gehrig, E. H., C. F. Clark, A. C. Peterson, and T. C. Rednour.
BPA's 1100-kv-dc test project; II--Radio Interference and Corona Loss, IEEE Transactions on Power Apparatus and Systems, vol. PAS-86, March, 1967, pp. 278-290.

14. Grois, E. S.
Prospectives for the Use of D-C Power Transmission in the U.S.S.R., Elektrichestvo (Moscow, U.S.S.R.), No. 7, 1960, pp. 86-89.

15. Highest Voltage Commercial Transmission in the World, IEEE Transactions on Power Apparatus and Systems, June, 1966. IEEE EHV-AC Transmission Conference, Richmond, Va., October 4-6, 1965.

16. Hill, H. L., and A. L. Kinyon.
A Laboratory Study of Switching Surge Flashover Characteristics of EHV Line Insulation, IEEE Transactions on Power Apparatus and Systems (Special Supplement), vol. 82, 1963, pp. 476-490.

17. Nesbit, William.
Electrical Characteristics of Transmission Circuits, Westinghouse Technical Night School Press, 1926.

18. Peterson, E. L., and H. P. St. Clair.
System Economics of Extra-High Voltage Transmission, AIEE Transactions, vol. 70, 1951, pp. 841.

19. Peterson, W. S.
Development of a Corona Loss Formula, AIEE Transactions, vol. 52, March, 1933, p. 62.

20. Poland, M. G., H. L. Hill, W. E. Scarborough, and P. W. Renner.
BPA's EHV Dc Tests: Part 1--Contaminated Insulator Tests; Part II--Outdoor Flashover Tests; presented at the 1966 IEEE Summer Power Meeting.

21. Smith, H. A., and H. P. Cadario.
Report of Visit to U.S.S.R. by Delegation from Canadian Electric Utilities, Hydroelectric Commission of Ontario, Toronto, Ontario, Canada, September 9, 1960.

22. Stevens, R. F.
Design of the Celilo-Sylmar 800-kv DC Line--BPA Section, IEEE Transactions on Power Apparatus and Systems, July, 1967.

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EXTRA HIGH VOLTAGE TRANSMISSION LINES

by

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AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Electrical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

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The generation and consumption of electric energy is increasing at such a rate that its transmission is becoming a serious problem. The solution discussed in this report is the use of extra-high d-c and a-c voltage for transmission.

Early developments, both American and foreign, are discussed. Predictions of future developments of EHV transmission are presented which are based on present-day growth trends.

Optimum solution of a given transmission problem may be defined as the solution with the lowest cost which will meet all the specifications and applicable standards, and insure the required reliability. In order to obtain the optimum solution, this report discusses the determination of the transmission voltage, conduction cross-sectional area and configuration, and insulation levels.

Comparisons are made concerning the use of a-c and d-c for EHV transmission. Problems associated with operation and control and conversion equipment are discussed.