New Means of Transmitting Electricity: A Three-Way Race

ENERGY

Because the consumption of energy in the form of electricity seems certain to increase drastically in the next two decades, the accepted method for transmitting it—namely, an overhead power line—needs serious examination. If the U.S. power consumption multiplies six times by the year 2000, as often predicted, is it tolerable to install five more lines for every one that exists now, or to replace each line with a gargantuan counterpart? More than 7 million acres (2.8 million hectares) of land are now set aside for overhead transmission, and, if the projected demand is met with more high-voltage towers, the needed acreage will probably double. Particularly in scenic areas, how much visual pollution is acceptable? In the large cities where most electricity is consumed, there is simply not enough available land, in many cases, for any enlargement of the power corridors. Power lines with greatly increased capacities, particularly lines that can be installed underground, appear to be needed.

Three new technologies for underground power transmission are being studied in addition to ways to improve the conventional overhead transmission lines. Transmission cables insulated with compressed gas, cables cooled to the temperatures of liquid nitrogen (called cryoresistive transmission lines), and cables cooled even more so that they become superconducting are all being developed as options to the conventional underground power lines (*Science*, 16 October 1970). The conventional cables are insulated with oil and paper, and operate at ambient temperatures.

No cryoresistive or superconducting cable has been installed commercially, but a short compressed gas cable is already being used by the Consolidated Edison Company in New York City. Because the market will clearly be large, research monies are being contributed by the companies that hope to sell the lines, as well as by the Electric Research Council, which is funded by private utility companies and the Department of the Interior, by the Atomic Energy Commission, and by the National Science Foundation. The situation now is an open race, in which it is still not known whether one or more than one of the new technologies will be needed.

The utility companies make a distinction between transmission systems, which transport large amounts of electric power from generating stations to major centers for consumption of electricity, and distribution systems, which carry energy to individual consumers. Lines operating at 138 kilovolts (kv) or more are usually considered to be transmission lines. Distribution lines operate at lower voltages, require much simpler technologies, and are being routinely installed underground in many cities.

Transmission is almost always done with overhead lines in the United States; only about 1 percent of the transmission lines are underground, and most of these are in the major urban centers between Boston and Washington. Overhead transmission lines are reliable, easy to repair, and quite efficient. (A 200-mile-long overhead transmission line operating at 345 kv delivers to the other end more than 98 percent of the power fed into it.) The power capacities of overhead lines can be improved by designing them larger for ultrahigh voltages (UHV), (voltages greater than 765 kv, the highest level now used in the United States). However, the towers to carry a UHV cable would be more than 150 feet tall, and would require a right-of-way more than twice as wide as the present transmission lines.

The future demand for underground transmission lines will almost certainly come in situations where overhead transmission is impossible, such as an offshore nuclear power plant, or where overhead transmission is unsafe or unsightly, such as the intersection of a transmission line with a superhighway, an airport runway, or another transmission line, or where overhead transmission is too expensive, such as in urban centers. Overhead transmission lines typically require 12 acres per mile. If the cost of land reaches $70,000 per acre, as it might in densely populated areas, the expense of land alone for an overhead line might be as great as the cost of a 345-kv underground cable ($840,000 per mile). The cost of right-of-way for an underground line is usually negligible. The pipes required can be laid in a 2-foot-wide trench, and the right to lay cable under the streets is often donated by the city. If land costs are not considered, however, an underground cable costs 6 to 20 times more than an overhead cable with the same power-carrying capacity.

High Capacity Underground Cables Needed

Where underground cables are needed to replace overhead lines, the problem is the types of cable now available are often too low in capacity. Underground transmission lines are limited because of the inability of the earth to absorb heat that is produced by the transmission of power through the cable. For a conventional underground cable designed to carry 230 kv the maximum power capacity is about 300 million volt–amperes (MVA), even if the trench is filled with special dirt with a high thermal conductivity. (About 300 MVA is the power needed by an average city of 200,000.) In order to transmit the amount of power that is now being routinely generated with steam turbines, many such cables would be needed. For instance, in Bratsk, Siberia, Russian engineers have built an underground system of two raceways, each holding six oil-filled cables. The total capacity is 2700 MVA. In the Russian system the cables are cooled with forced air, but even more efficient methods of cooling, such as recirculating the oil through a heat exchanger, will be necessary. Even with improved cooling, oil-filled cables will probably have only twice their present capacity.

The advantage of the newer cable technologies is that heat dissipation can either be reduced, in the case of the compressed gas cables, or effectively controlled, in the cases of the cryoresistive and superconducting cables. The benefit is not that a greater fraction of the power reaches the other end but that much more power can be carried without exceeding the tolerances of safety. For example, in a cryoresistive line the resistance of the conductor is reduced by a factor of 10 when the line is cooled to the temperature of liquid nitrogen (77°K). However, because of the laws of thermodynamics, all refrigerators become much less efficient at low temperatures. In fact, a typical refrigerator would use about 9.5 watts of power to pump 1 watt of heat away from the cold cable. Thus the savings in heat dissipation are canceled by the inefficiency of a very-low-temperature refrigerator.

A similar effect occurs with superconducting transmission lines. The resistance of a superconducting line is zero for direct currents (d-c); but for alternating currents (a-c) the magnetic field from the current causes a heat loss which must be pumped away with a refrigerator. The total loss in an a-c superconducting cable, after the inefficiencies of the refrigerator are taken into account, will probably be about the same as the losses in an overhead transmission line operating at ambient temperature (but certainly less than the losses in the present underground cables).

Figure 1 indicates the power capabilities of the conventional oil-filled cables and the three alternate types of cable. The maximum capacity of the conventional cable, about 1500 MVA, is clearly exceeded by the other types. The superconducting cable has the greatest potential for carrying large amounts of power. For most designs, it has been estimated that a single superconducting cable could carry more than 10,000 MVA, the power needed for all of New York City.

Underground cables are not without some severe limitations. The configuration of any underground line (namely, an arrangement of two concentric conductors) introduces a capacitance that is very much larger than that of overhead lines. The capacitance induces a current (called a charging current) that does not contribute any effective power, but nonetheless produces large heat losses. The capacitance of conventional cables is particularly great because of the choice of insulation and because they are made very compactly. As a result, conventional underground cables have a large charging current, which limits the usable length to about 20 miles.

Compressed gas cables have much lower charging currents and therefore can be used to carry more power for longer distances (over 200 miles). Because of the superior electrical properties of sulfur hexafluoride, the gas used as an insulator, the heat dissipation is significantly less than that from a conventional cable. However, compressed gas cables have several dis-

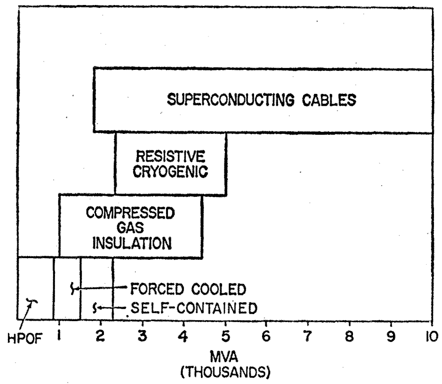

Fig. 1. The power-carrying capabilities of new underground transmission systems. High-pressure oil-filled cable (*HPOF*) is the conventional type.

advantages—not the least of which is cost—that have limited the longest installation so far to 1300 feet. For example, according to H. C. Doepken of the High Voltage Power Corporation, Westboro, Massachusetts, a compressed gas cable capable of carrying more than 2000 MVA of power (designed for 500 kv) would cost about $2 million per mile. Each of the three phases of a 500-kv line would be a rather large, rigid aluminum pipe 20 inches in diameter. Individual sections 40 feet long would be welded together at the site of installation, a time-consuming and costly process. Because the three pipes are laid side by side, compressed gas lines require very wide trenches. An 8-foot-wide trench would be required for the 500-kv line. Some utility officials think that the size of the trenches alone may prohibit the use of compressed gas cables in many urban areas. However, the great advantage of the gas cables is that they are available today. Doepken and others think that

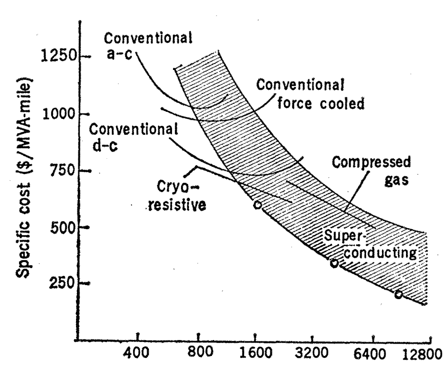

Fig. 2. The costs of various types of underground transmission lines. The cost of high-capacity overhead lines is about $100 per MVA per mile (based on the 1971 installation of a 765-kv line with 3000-MVA capacity by the American Electric Power Company).

it will soon be possible to double the capacities of compressed gas lines by simply cooling the outer cable jackets with water. Whether the size of the trench needed for a compressed gas line of very high capacity could be reduced to something less than the width of a city street is still to be determined, but High Voltage Power Corporation and other companies are trying to develop a compressed gas cable with all three phases in a single jacket.

A plan for a gas-insulated transmission line somewhat different from the compressed gas lines now in use has been proposed by Benjamin M. Johnson of the Battelle Pacific Northwest Laboratories, Richland, Washington. If an insulating gas other than sulfur hexafluoride were used, the gas could be circulated into the cable in the liquid state, then evaporated by the heat of the conductor to carry off the heat dissipated electrically, and finally recondensed into liquid in an external cooling unit. The system would require cooling units at frequent intervals, as would the cryoresistive and superconducting cables, but it is likely that no new technological development would be required for them. The Battelle proposal is not yet being commercially developed, however.

Cyroresistive transmission lines would solve the power limitations of conventional cables by cooling the system with external refrigerators, but the proponents of the cryoresistive technology hope that by avoiding the extremely cold temperatures needed for superconductivity they can produce a working transmission line sooner and with less research and development. At the General Electric Company in Schenectady, New York, a 500-kv cryoresistive cable is now undergoing laboratory tests. It is a flexible cable with aluminum conductors, which will be cooled to the temperature of liquid nitrogen and insulated with a synthetic paper (Tyvek). It is expected that refrigerators will be installed every 7 miles, so the cooling network will be about as extensive and complex as the electrical network. The capital costs of the refrigerating system are certain to be quite large, and the reliability of the system will have to be proven through an extensive program of testing followed by careful selection of the locations of the initial commercial installations.

Superconducting transmission lines will be made of metals or metal compounds that have no resistive losses at very low temperatures. All the superconducting cables tested have been made of niobium, a metal that is rare, expensive, and much more difficult to fabricate than aluminum. Because niobium must be cooled to temperatures below 9°K in order to become superconducting, the problems of refrigeration and thermal insulation will certainly be greater than the analogous problems for a cryoresistive line. However, superconducting cables could carry very large amounts of power, and the cable would be very compact. In some estimates the diameter of a 10,000-MVA cable is as small as 60 cm. The cost of a superconducting cable would certainly be immense, but it would transmit so much power that the cost per kilowatt is projected to be less than the cost of conventional underground cables (Fig. 2). The cost estimates for superconducting cables of various designs vary by a factor of 2 or more, a reflection of the uncertainties about the best design for a cable and probably an indication of the length of time that will pass before superconducting cables are well-tested, reliable products. Nonetheless, the AEG-Telefunken company in Frankfurt, Germany, is testing a flexible superconducting d-c cable that may soon be commercially available.

Choice of a Superconductor

Researchers in the United States, however, have not yet reached a consensus about the best material for a superconductor. Robert W. Meyerhoff and associates at the Linde Division of the Union Carbide Corporation, Tarrytown, New York, propose a rigid cable with a niobium superconductor, which would have either liquid helium (the coolant) or a vacuum as the insulating medium. According to Meyerhoff, such a cable could be commercially available by 1984.

Niobium has the advantage of ductility and low electrical losses for alternating current, but it will not carry a severe fault without losing its superconducting properties (a-c transmission lines must be able to sustain a tenfold current overload). A niobium-tin compound (Nb_3Sn) is superconducting at higher temperatures (up to 18°K). Cables with a niobium-tin superconductor should be able to sustain a fault without losing transmission capability. Because of the unusual properties of helium at the temperatures necessary for superconductivity, the improved efficiency of a refrigerator operating at the higher optimum temperature for niobium-tin would more than compensate for the greater electrical losses of niobium-tin. One of the disadvantages of niobium-tin, as compared to niobium, is that its physical properties, such as ductility, are poorer.

Niobium-tin superconducting transmission lines are being studied at the Brookhaven National Laboratory, Upton, New York, by Eric Forsyth and associates and at Stanford University, Palo Alto, California, by Theodore Geballe. The Brookhaven study, which is supported by the National Science Foundation under the Research Applied to National Needs (RANN) program, proposes a flexible cable made with a helical conductor and a solid dielectric. The Stanford design is similar, but the superconductor is fabricated in 50 or 100 thin layers rather than in 3 or 4 layers, as in the Brookhaven design.

Direct Current for Long Distances

Direct current superconducting transmission lines are also being studied as a possibility for power transmission in the future. Direct current transmission is advantageous for underground transmission because the same line will generally have twice the capacity for d-c current as it does for a-c current. However, expensive convertors are necessary at both ends of a d-c line in order to couple it into the normal a-c network. Direct current lines have seldom been used in the United States (although more often than in Europe). For very long transmission lines, however, the savings in the cost per mile of the line will more than compensate for the cost of having convertors at both ends (about $30 per thousand watts of transmission capacity). The Bonneville Power Administration has an 850-mile-long d-c transmission line (overhead) from Oregon to Southern California.

Direct current transmission by superconducting lines would involve no electrical losses at all, so the heat load for the refrigeration system would be far less than the heat load of an a-c line. The refrigerators would only have to compensate for the relatively small amount of heat that leaks into the cable because of inefficient thermal insulation. The electrical losses in convertors would be about 1.25 percent at each end, however, an amount comparable to the losses in a 200-mile a-c overhead line. E. F. Hammel and associates at the Los Alamos Scientific Laboratory, Los Alamos, New Mexico, are studying various designs for superconducting d-c transmission lines under the sponsorship of the Atomic Energy Commission. Estimates of the minimum length of a d-c transmission line that will break even with the cost of convertors vary, with figures between 31 and 250 miles (50 and 400 kilometers) mentioned, but it seems likely that the economic constraints that make all underground transmission unattractive in open country will probably prevail for several decades. However, d-c lines have certain advantages over a-c lines that make them desirable as interties between regional power systems. Superconducting d-c lines may be needed for such interties.

Any or all of the new technologies could produce systems that would be less expensive than conventional underground transmission lines, if built with large enough capacities. However, very-high-capacity transmission lines, 10,000 MVA or more, could invite problems with stability in the electrical networks and new possibilities of sabotage.

Greater Costs Foreseen

Unless there are major breakthroughs —which are not now discernible—in research on these new cables, the costs will be at least three and probably more than five times the costs of overhead cables, even of the largest cables. Underground cables now represent more than 10 percent of the capital investment in transmission facilities in the United States, although they make up only 1 percent of the network. The greatest uncertainty for costs of electrical power transmission in the future is the extent to which underground transmission will replace overhead lines.

The transmission network in the United States will have to undergo major changes if it is going to supply three to six times more electricity at the century's end. The short-term demand for electricity is influenced by many factors (*Science*, 17 November 1972), one of which is the expense and extent of underground transmission. Further in the future, it is possible that decentralized power production (by photovoltaic cells, for instance) could alleviate the demand for more electrical transmission or that cheaper means of energy transmission (such as piped hydrogen) might supplant the electrical transmission line. But for the next decade or two, it appears that the rising costs of electrical power transmission will add to the ever-increasing price of raw energy.

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