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Using Conventional Elpipes For Long Distance Transmission

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Overhead transmission lines grow more controversial each year, while at the same time, the economic need to transport bulk power grows, fueled in part by the rapid development of utility-scale wind farms remote from population centers. It is difficult to site new overhead power lines of any capacity, and it is particularly difficult to site new high voltage overhead lines, which are aesthetically overpowering (Figure 1).

Figure 1: Relative Scale of 745kV AC Line to buildings

Most of these objections can be overcome by placing long-haul (100 km and over) transmission lines underground. These are the options for achieving this:

- Conventional cables (maximum 500kV at present)
- Superconducting cables (maximum 200kV at present)
- Gas Insulated Lines (GIL) (maximum 800kV)
- Solid-insulated electric pipelines based on metallic conductors, “elpipes;” (max voltage 800kV)

Of these options, underground cables have a significantly lower power transfer capacity, and cost many times more than overhead power lines, so they are rarely used except in and around cities. Cables can be used to deliver AC or DC power, but AC runs are limited to 50 km or so (which is short in this context) before capacitive charging currents rise to the point that the cable requires expensive reactive compensators to deliver useful power.

Cables can currently transmit DC power hundreds of kilometers, limited mainly by economics and the need to maintain acceptable I^2R losses. Cables need to be wrapped on a drum for delivery from the factory to the installation site. The required bending radius limits the cable diameter, and thus the conductor size and insulator thickness, and therefore also the capacity. Waste heat removal is a problem for high power cables. All the available flexible electrical insulation materials are also good thermal insulators, so as the voltage goes up, the thicker insulation required to withstand the voltage reduces the thermal dissipation capacity of the line per meter. Thus, increasing the voltage of a thermally-limited buried cable does not increase the power capacity proportionately to the voltage increase.

Typically an overhead power line can carry four times as much power for each doubling of its voltage (at constant transmission efficiency). For passively cooled cables, doubling voltage less than doubles capacity (because the reduced thermal dissipation capacity means the current must be reduced at higher voltage). About 1.1 GW per cable pair is the limit at present; and such cables must be buried shallowly (<30 cm), or in special thermally conductive sand to achieve these power levels. If the cables are actively cooled by a circulating coolant fluid, transfer capacity can be increased to about 1.5 GW/cable pair. At present, the maximum rated voltage for cables is 500kV, though breakthroughs in nanocomposite insulation technology (see US patent 7,579,397, now licensed to Dow by EPRI) promise to allow for thinner insulation layers (capable of 20kV/mm as opposed to the present 10-12kV/mm design voltage gradient) which will in the future enable an 800kV polymer-insulated HVDC cable.

Superconducting power cables, which were described by Jack McCall of American Superconductor in the November/December issue of Electricity Today, have been getting a lot of attention and R&D funding. High power superconducting DC cables have yet to be deployed, though relatively high power (~0.6 GW), high voltage AC superconductor cables have been in operation for a number of years. The cryocooling systems, though complex, are included in the cost of superconductor electricity pipelines as quadruple redundant systems with a variety of backup and service features. Though such extensive cryocooling has never been deployed, the engineering is sound and all of the core components have either been fully simulated or demonstrated. Nonetheless, the complexity per se of superconducting DC transmission makes proving reliability a difficult process that must occur in stages over decades. Still, the unique property of zero electrical resistance means that superconducting cables will eventually be important for long distance applications.

Gas Insulated Lines (GIL) are a proven alternative for high capacity underground power lines, but though they have been available for 35 years, there has so far been no installation longer than 3.25 kilometers, due to the high cost per km. These designs rely on sulfur hexafluoride (SF_6) gas, which is a potent greenhouse gas, for insulation. GIL lines are the only underground option that is feasible for long distance AC power transmission. This is because of their low capacitance per km; though not quite as low as an overhead line, it is low enough that more than a hundred kilometers of GIL could be used for AC transmission before capacitive charging currents become an issue. In fact, though GIL can theoretically be used for either AC or DC transmission, all the commercial installations worldwide are for AC at present. Many vendors offer GIL products, but Siemens is the current technology leader.

The first three options discussed above (cables, superconductor, and GIL) are significantly more expensive than overhead lines in terms of dollars/(GW-km). There is a fourth alternative for underground bulk power transmission that deserves to be part of the discussion: electric pipelines based on conventional conductors, "elpipes" for short. Figures 2a and 2b show two different concepts for HVDC elpipes. Practical elpipe designs for long distance transmission must be DC and share these features:

- Significantly more conductor is used per km than is feasible for an overhead line or a cable;
- Resistance (ohms/km) & losses (watts per meter) are much less than an overhead line or a cable;
- Waste heat removal limits capacity except for actively cooled (from the inside) designs;
- Elpipes consist of shorter pieces than cables, which must be transported and spliced;
- Since a large number of splices are required, they must be simple, very reliable, and cheap.

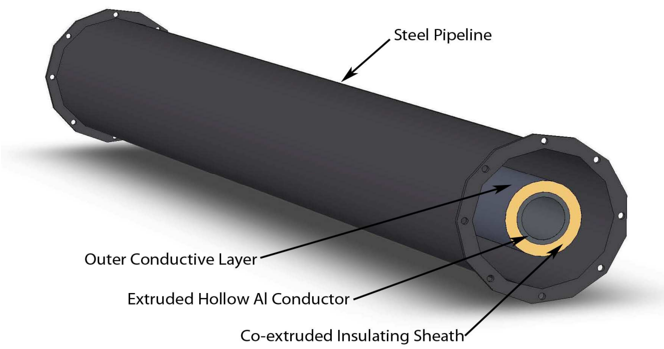

Figure 2a: Directly Buried HVDC Elpipe

This elpipe has 50 cubic meters of aluminum per km; a transmission line is comprised of two such elpipes running at +800kV and -800kV, and has 1.4 ohms/1000 km (both ways). The transfer capacity for a pair of these elpipes, based on 0.8% loss/1000 km, is 15 GW; at full capacity, 123 watts per meter (for the pair) are produced from I^2R losses.

Elpipes represent a paradigm shift for long distance transmission in several ways. Because they are not wrapped on a reel for transport, elpipes can use far more conductor than cables or overhead power lines. Although the words "electric pipeline" have been used to describe many different versions of high capacity power lines (even including overhead lines), elpipes in their simplest embodiment (Figure 2a) really do resemble a gas or oil pipeline. The key issues to resolve to make this approach practical are low cost and reliable splices, efficient removal of waste heat produced from resistive losses, and handling thermal expansion.

Electric Pipeline Corporation, the startup company formed by the authors of this paper to commercialize this approach, has developed proprietary methods to accomplish low cost splices at high voltage levels, and enhanced insulations that facilitate efficient heat removal. Although waste heat removal limits underground cables to a maximum transfer capacity of about 1.1 GW, directly buried elpipes as per Figure 2a can be designed to transmit up to 15 GW and still be passively cooled underground. Simple strategies such as backfilling with conductive sand can boost the capacity of directly buried elpipes significantly, as can simply using more conductor (additional metal can be inexpensively added to the inside of the elpipe conductors). Part of the advantage that elpipes have over cables is that the hollow pipe shape of the conductor gives more surface area through which to dissipate the waste heat; however the bigger factor is simply that the design enables the use of a lot more conductor than is even feasible for a cable, typically 10-50 times as much. The particular design shown in Figure 2a has a 15 GW transfer capacity at 0.8% transmission loss/1000 km. (This is about one sixth the transmission loss per km of the best overhead transmission lines of today, and is comparable to the efficiency of superconducting lines, after accounting for the energy cost of cryocooling.) Waste heat due to I^2R loss at the design power level (15 GW) is only 123 watts/meter (for the pair of elpipes required to transmit power), well within the ability to dissipate passively through most soils. (Control of waste heat is the main reason for the high efficiency of the line: it is more cost effective to prevent the production of waste heat by using more conductor than to implement the special design features needed to remove a larger amount of waste heat.) Raw materials cost per km for this elpipe (including both directions) are:

Conductor (100 cubic meters/km aluminum AA8030 alloy, extruded)	$ 890,000
Insulator (crosslinked polyethylene)	$ 460,000
Steel Pipeline Shell (24" pipe, ½" wall)	$ 340,000
Total Raw Material Cost per km (excluding joints)	$1,690,000 (US dollars)

The full price of completed projects (excluding only the AC/DC/AC converter stations) will depend on a number of factors, but would average 3 times the material costs if present market prices prevailed. Though this is a large number ($5 million/km), it is a bargain compared to cost projections for underground superconducting lines, or gas-insulated lines with equivalent capacity. It is also likely that if there was a commitment to build out an HVDC supergrid, competitive pressures would greatly reduce the cost of the converter stations (these costs are nearly equivalent for any HVDC line, and at prevailing rates can constitute 50% or more of the cost of an HVDC link).

An interesting comparison between an elpipe versus an overhead line or a buried cable conductor is to look at what fraction of the cost of the transmission line is for the conductor per se; in an overhead transmission project the fraction of the money spent on the conductor per se (aluminum purchased by the wire manufacturer) is typically around 2% of the project cost; for a cable system, conductor purchase price would proportionately be even less if cables were made from aluminum (but generally copper is used instead). In contrast, for an elpipe, 20-25% of the cost of the line goes to purchase conductor, which is economically more efficient because only the conductor actually carries current.

To implement elpipe designs with higher passive heat dissipation (above 200 watts/meter of elpipe), one has to ensure efficient heat removal; Figure 2b shows a design for a pair of electric pipelines that are integrated into a module which includes an upper road surface for reliable heat dissipation. (The road must be a thermally conductive material that preferably reflects most of the incident solar radiation while also being a good emitter of thermal infrared.) This upper surface could be used as a bike path, or a maintenance road.

The particular dimensions of Figure 2b correspond to a transfer capacity of 10 GW at 1.2% I^2R loss/1000 km; this goes up to 12.8 GW at 1.6% loss/1000 km (approximately the thermal limit for transmission for this specific design). This is a significantly lower range of losses per km than for an 800kV DC overhead transmission line, with about twice the capacity.

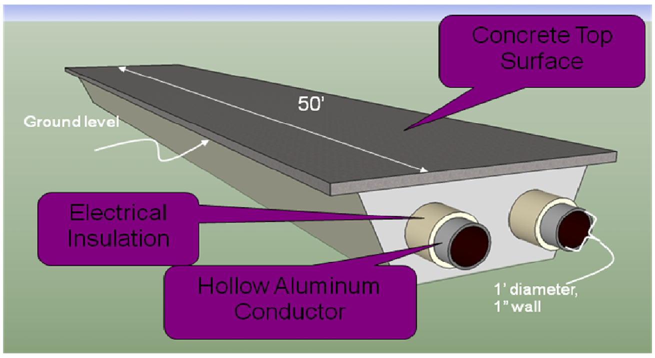

Figure 2b: Elpipe Pair Integrated into Road/Heat Dissipation Module

This electric pipeline has 45 cubic meters of aluminum/km (including both conductors), and has 3.15 ohms/1000 km (considering both directions of the flow of current); energy transfer capacity at 1.2% I^2R loss/1000 km is 10 GW; this goes up to 12.8 GW at 1.6% loss/1000 km.

Passively cooled elpipe designs like that of Figure 2b can work up to about 40 GW of capacity, by using more conductor than the design of Figure 2b. Internally-cooled elpipes can go to even higher capacities, limited only by the cost of conductor; 200 GW connections are economically feasible for internally cooled aluminum conductor elpipes; if sodium (the most cost effective conductor) were used, elpipes up to 1000 GW (one terawatt) are feasible to transmit power coast-to-coast economically. Because of reliability concerns, it is unlikely that power lines designed for more than 20 GW will be deployed in the near future. Eventually though, when circuit breakers capable of handling 200 GW are developed, deployment of 200 GW coast-to-coast circuits (as in Figure 3) may prove to be the least expensive way to implement a continental grid. In the case of elpipes or any other transmission line based on metallic conductors which are limited by heat dissipation, adding twice as much metal increases transmission capacity only by a factor of the square root of two. (This is because heat dissipation scales with I^2R, while power transmitted scales with VI.) Therefore at sufficiently high capacity, internal cooling of elpipes is required for optimum utilization of the conductor and optimal economic efficiency.

It is highly desirable for a power line to have the ability to be overloaded for a short time, for example during an outage of another line, or during the peak load time of day and/or day of the year. In general, this is a favorable property of overhead lines, which can be overloaded by high margins during upset or abnormal conditions (several times the normal load can be carried for long periods of time with no damage, if line sag and annealing are not issues), though with lower delivery efficiency. By contrast, underground cables in general have low overload capacity, since they are normally constrained by heat dissipation; basically, their overload capacity is determined by how long it takes for adiabatic heating of the cable from normal operating temperature to the maximum safe operating temperature, usually less than 10 minutes at double the rated energy flow. Elpipes are an interesting in-between case, because though they are also constrained by heat dissipation, the heat capacity of the line is substantially higher than for a cable (simply because they use several times more conductor mass per amp carried); for a typical elpipe operating at a transmission loss level of 1.2% I^2R loss per 1000 km on a hot day, it is possible to carry twice the normal amount of power for 1 hour without incurring any permanent damage.

The practical limit for conventional, overhead transmission has nearly been reached (new 800kV DC lines in China will transmit up to 6.4 GW per line, around 2000 kilometers), yet there exists the need for even more transfer capacity. The idea of a conventional conductor based “electric pipeline” was proposed by Roger Faulkner in 1991 testimony to the Wisconsin Public Service Commission’s Advance Plan 6 hearings; it was a back-burner project until recent advances made it seem more feasible.

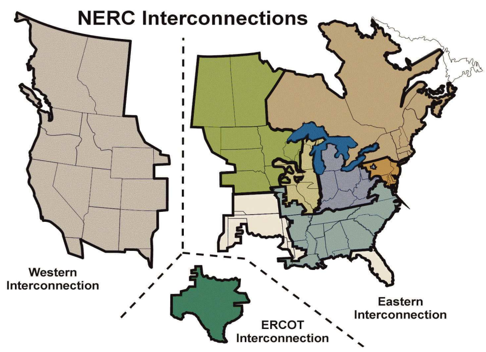

Figure 3: NERC Map Showing Synchronous Regions

It is important that an HVDC grid operate at a single voltage because (unlike AC) there is no economical DC/DC transformer. Such a grid cannot be AC, because North America is too large an area to form a single stable synchronous grid. At present there are three synchronous areas in North America.

Figure 4 shows a long-term vision of a supergrid for North America (only the largest lines are shown). Such a grid cannot be AC, because North America is too large an area to form a single stable synchronous grid. It is important that an HVDC grid operate at a single voltage because (unlike AC) there is no economical DC/DC transformer. We envision a future HVDC supergrid containing both superconducting links and elpipes. Figure 4 shows two crossing (but not necessarily electrically connected) superconducting lines that together connect to only four points on an elpipe grid. These links would carry most of the coast-to-coast electricity under normal conditions, yet the grid can withstand the loss of either or both of the superconducting links, due to the redundant elpipe links. Deploying two independent superconducting links would be advantageous from a system stability point of view, whereas connecting the two superconducting circuits where they cross is better from an energy conservation point of view. In fact, if the two superconducting links are not cross-bonded, there would be four redundant coast-to-coast links in just the major power lines of Figure 3, and smaller connecting lines (not shown) would provide a mesh to give even another level of redundancy for the coast-to-coast connection. A key to this proposal of a hybrid grid would be to boost the maximum voltage withstand of cryogenic HTS cables to 800kV.

Figure 4: Hybrid North American HVDC Supergrid

These are major 200 GW lines: the blue lines are superconducting links (5400 km total), and the red lines are elpipes that form a loop around North America (about twice the total length of the superconducting lines). This would clearly require international cooperation.

Such a grid (with or without the superconducting lines) would make it possible to share wind-generated electricity over the entire North American continental area, which allows geographically dispersed wind sites (Great Plains, the coasts, Great Lakes, Hudson's Bay for instance) to be aggregated together to smooth out regional fluctuations. Additional resource smoothing would occur since such a supergrid would also interconnect North American pumped storage assets. Wind, solar, and other intermittent renewables would become firm, baseline generation resources. New renewable generation and storage sites could be located where physical resources dictate. Such a grid enables market access for remote tidal energy in Hudson's Bay as well as for Arizona solar power. (There is a reliability advantage in pulling together multiple renewable energy sources.) Such a supergrid would also allow nuclear power to be sited away from population centers, in locations where waste heat will cause minimal environmental disruption or perhaps positive benefits, in places where competition for water resources for cooling are minimal (Hudson's Bay, for example), and/or where there is little opposition from local residents.

Unlike a purely superconductor-based coast-to-coast supergrid, though, if either or both of the superconducting links is lost in the proposed hybrid grid, there is enough capacity in the elpipe portion of the grid of Figure 4 to "take up the slack" without a system crash. In this scenario, loss of a superconducting line would cause a sudden reduction of efficiency of coast-to-coast transmission that would look to the system like a major generation asset suddenly dropping out; this would be far more easily accommodated by the hybrid grid of Figure 3 compared to the scenario where the coast-to-coast link is simply broken. As long as the abrupt change in delivered power remains within safe limits, loss of either or both of the superconducting lines need not cause a widespread outage, even in the scenario that under normal conditions, the superconducting line may be carrying hundreds of GW. The superconducting lines similarly provide redundancy to the elpipe based supergrid, while increasing transfer efficiency. Such a hybrid design would capture most of the efficiency benefit from using superconductors in a continental scale supergrid, without requiring as a prerequisite that extreme levels of reliability be proven for DC superconducting lines prior to building a supergrid. However, in order to implement such a hybrid scheme, the voltage withstand in cryogenic superconducting cables will have to be improved from the currently feasible 200kV to the 800kV level that makes the most sense for a conventional-conductor based HVDC grid.

In its final implementation, the HVDC supergrid will probably incorporate all of the 800kV transmission options where appropriate. Figure 4 illustrates only the continental-scale electric pipelines that make up the backbone of the proposed hybrid continental supergrid. This consists of a combination of two kinds of major trunk lines: a 200 GW-capacity actively cooled elpipe loop around North America (red) and two superconductor links (blue, also 200 GW). Not shown in Figure 3, is a mesh of smaller 1-20 GW 800kV powerlines that can be overhead, cables, or small passively cooled elpipes. These smaller lines provide another level of redundancy in case of a main loop failure.

We have sought in this article to provide a balanced view of how a continental scale HVDC grid of the future will look. We are not promoting elpipes as a panacea for long distance transmission. Elpipes are practical for transmission of 5-200 GW at the continental scale (1.25% loss/1000 km), but are at present most competitive in the 10-20 GW size range. Elpipes will likely form one part of an HVDC grid that also includes superconducting lines, overhead transmission, and underground cables. Each technology will find its niche.

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