Elpipes for the High Capacity Backbone of an Asian Grid

Roger Faulkner, President;
Electric Pipeline Corporation,
One Marina Park Drive, Boston MA USA
roger.faulkner@elpipe.com

***Abstract**: Elpipes are polymer-insulated underground HVDC electric pipelines based on metallic conductors. Elpipes use relatively rigid extruded conductors designed for higher capacity and efficiency than are practical for overhead power lines. Rigid insulation may be used. In this paper, we discuss the technical trade-offs for elpipes, and application of elpipes to linking load centers to remote dispatchable hydro power, energy storage sites, and large dispatchable loads, to achieve load leveling through non-local storage and dispatchable loads, via the HVDC grid. Elpipes with voltage source converters (VSC) enable placing many AC/DC power taps on a single HVDC loop. It is advantageous to build up a continental scale HVDC grid from local loops that tie together 10-20 taps.*

Keywords: elpipe, HVDC, VSC, LCC, GIL, HTS, GRIDS, load leveling, supergrid, Trans-Siberian Railroad

0 INTRODUCTION

Elpipes use far more conductor than cables, and therefore can carry more energy, but also have more splices. The high efficiency of elpipes (~1% I^2R loss per 1000 km) is motivated in part by the need to minimize heat dissipation while maintaining passive cooling [1]. Figure 1 shows a cutaway view of an elpipe segment module, while Figure 2 shows how segment modules and splice modules are combined to create an elpipe that can be installed in a curved pipe. The cost efficiency of metallic conductors varies significantly, with sodium being the least expensive conductor, followed by aluminum (about seven times as expensive as sodium on an equal conductivity basis), followed by copper [2] (see Figure 3).

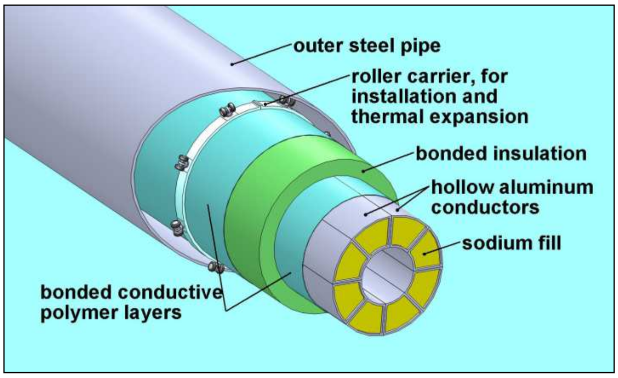


Figure 1. Cutaway view of elpipe segment module

1 ELPIPE FEATURES

A recent paper discusses insulation aspects of HVDC elpipes [3]. A recent PCT patent application [4] discusses numerous aspects of elpipe design, including designs that use sodium-filled hollow keystones [5] (Figure 1) for the pipe-shaped parts of the conductor segment modules (which comprise most of the total conductor mass, and are joined by splice modules). In this case, all sodium is deployed within strong metallic shells, which isolate the sodium from the environment, and from the sodium in nearby segments. (Not shown in Figure 1 are the compressible bladders within the sodium which compensate for melting expansion.)

Elpipes can be fully underground (Figure 1), installed at the surface, or above ground. An elpipe installed at the surface could go to at least 30 GW with passive cooling. It is also possible to achieve efficient heat shedding from deeply buried, high capacity elpipes by using heat pipes to link buried elpipes to radiators for the waste heat at the surface.

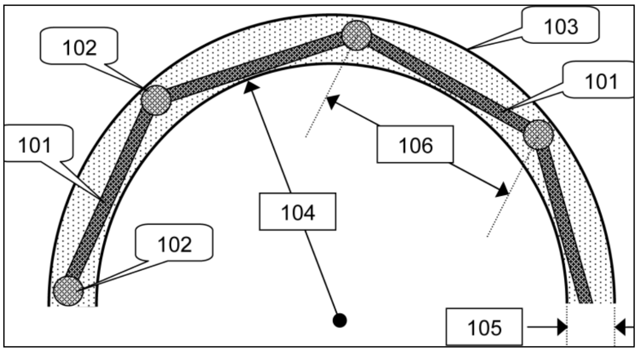


Figure 2. Elpipe Segment and Splice Modules

The segment modules 101 are connected through the splice modules 102, which have a connected length 106. The minimum radius of curvature is 104 at the inside of the conduit, and increases if the modules101 get shorter, or if the conduit diameter 105 increases.

Actively (but non-cryogenically) cooled elpipe designs can theoretically go to transfer capacities above 200 GW. Such high capacities would require full redundancy to meet reliability standards, and (like any HVDC grid) would require new HVDC circuit breaker technologies that are yet to be developed [6].

Waste heat dissipation limits the steady state energy transfer capacity of any ohmic conductor, but not high temperature superconducting cables (HTS). The need to dissipate waste heat makes it difficult to bury any HVDC line deep underground compared to HTS cables; on the other hand the simplicity of elpipes is expected to make them more reliable than HTS links.

Elpipes have high thermal overload capacity compared to conventional cables due to their large heat capacity per unit ampacity and because they are hollow, which gives more surface area to shed waste heat to the environment. Elpipes can operate for several hours at double their normal power capacity prior to reaching the maximum temperature of the insulation [2], compared to about 10 minutes for an underground cable. The thermal overload capacity extends to four hours or more if elpipes use sodium for a large fraction of total conduction, because sodium melts at 98° Celsius, controlling temperature until all the sodium is melted.

Elpipe construction is mostly conventional, and requires no fundamentally new developments except the splices, which at this stage are proprietary to Electric Pipeline Corporation (EPC) and cannot be described in detail yet, though my recent PCT patent application [4] does give more detail on the splices. A previous paper [7] examined how elpipes could fit into an HVDC grid that also incorporates other technologies such as overhead HVDC, gas insulated lines (GIL), flexible cables, and high temperature superconducting (HTS) cables. It is highly desirable to devise a future HVDC grid around a single operational voltage (500-800kV), since DC/DC transformers are quite expensive. (A breakthrough is needed on HTS-HVDC junctions to enable interoperability of HTS with HVDC in the 500-800kV range.)

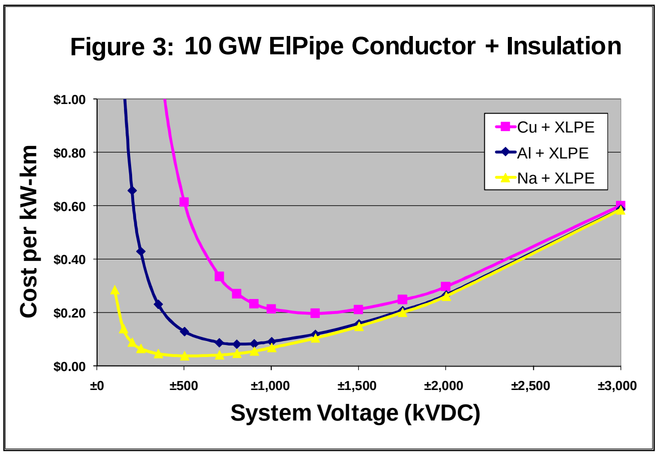
2 ELPIPES: TECHNICAL CONSIDERATIONS

Figure 1 shows a cut-away view cut through the middle of a segment module of one pole of a bipolar elpipe HVDC system. The conductor/insulator boundary lies within the polymer phase, but unlike HVDC cables, the insulation layer is not bonded to the conductor (except at one point). This feature allows differential thermal expansion of the insulator and conductor without generating high mechanical stresses, and also separates the manufacturing of the elpipe segments into three separate components, the inner conductor, the polymer insulator (containing the conductor-insulator boundary), and the conduit. Each has its own quality control methodology, and unlike the case for HVDC cables, a failure in the insulating pipe during testing does not require replacement of the inner conductor. This enables much higher test voltage for the insulator pipe with economically acceptable higher failure rates. By failing the weakest parts of the insulating pipe prior to assembly of the elpipe segments, a more reliable composite segment may be achieved.

Passive waste heat removal limits steady-state capacity for any fully buried transmission line based on conventional conductors. For buried, truck-transportable HVDC cables, waste heat dissipation limits maximum transfer capacity to about 1.1 GW per circuit at present, though anticipated cable insulation improvements [8] may take this up to about 3 GW per circuit in the next ten years for crosslinked polyethylene (XLPE)-insulated cables. Elpipes use 3-18 times more metal/ampere than HVDC cables or overhead power lines, and so have higher efficiency. Even with current XLPE insulation technology, a buried elpipe circuit (Figure 1) would be capable to 12 GW, and a surface-installed version would be capable of transferring up to 30 GW.

2.1 Design Voltage of Elpipes

Elpipes are envisioned as future components of a continental scale HVDC grid that will lie "below" the AC grid. Selection of an operational voltage for such a grid involves many considerations, including ease and cost of interfacing with the AC grid. Figure 3 shows the cost of conductor + insulator for three candidate conductors: copper, aluminum, and sodium, all insulated with conventional XLPE, with maximum voltage gradient 10 kV/mm. All elpipes were sized for 10 GW per circuit @ 1% I^2R loss/1000 km. Market prices for the metals and XLPE were used.



The curves of Figure 3 show capital cost for two important components of the elpipe: (conductor + insulator) versus DC voltage. The more expensive the conductor is, the higher the cost for conductor + insulator, and the higher the economic optimum operating voltage (sodium: ±500 kV; aluminum: ±800 kV; copper: ±1250 kV). Transmission capacity (10 GW) and efficiency (1% loss I^2R loss/1,000 km) were held constant in Figure 3. At any particular voltage the outside conductor radius is the same for copper, aluminum, or sodium for Figure 3; this is required for equivalence in shedding waste heat. (The pipe wall radius ratios, inside conductor pipe radius/outside pipe radius were held constant for each metal: .825 for copper, .683 for aluminum, and .302 for sodium.)

It is very interesting that the cost for electrical energy transfer using sodium as the conductor is low over the entire range of voltage from 325-800 kV, below the lowest cost for aluminum over this entire range. I am aware of the technical difficulty of working with sodium, and also the public relations nightmare it would be to propose a sodium-conductored elpipe technology in the US or Europe. Nonetheless, this is clearly the low cost solution. It is possible to deploy an aluminum elpipe with internal voids that can be flooded with sodium to increase the capacity of the line at a later date.

Present National Electric Safety Code rules in the US [9] allow no more than 30 minutes of emergency operation of an HVDC system in monopolar mode with ground return, but if the ground return can go back through the conduit wall or a special moderate voltage elpipe for emergency ground return, then it is feasible to operate for long periods in a monopolar mode (to deliver nearly the same amount of power for at least several hours, though with higher losses; and thereafter to deliver half the full capacity power indefinitely) while the faulted leg of the bipolar HVDC system is repaired. In this case, the voltage withstand capability of the insulation between the ground return and ground only needs to be 40kV or less. I do not know whether ground return during a fault will be allowed for longer periods in China; my opinion is that long term ground return of DC should be allowed, because (unlike AC) the power goes deep rather than along the Earth's surface.

A CIGRE committee has been studying the problem of what common HVDC voltage should be adopted for continental scale HVDC grids; one key consideration is the ease of interfacing with existing AC grids. It is likely that the selected design voltage will be between ±(500-800)kV, possibly ±640kV. This voltage (640kV) corresponds to the lowest cost operating voltage for a mixed conductor (Na/Al) hybrid, as in Figure 1.

2.2 Insulation of Elpipes

Insulation for elpipes need not be flexible, as is required for cables. A spirally wound insulation comprising alternating layers of polymer film insulation coated on each side with thin film semiconductor has been disclosed [3], [4]. Glass or ceramic insulators have also been disclosed [4] for the rigid insulation of Figure 4.

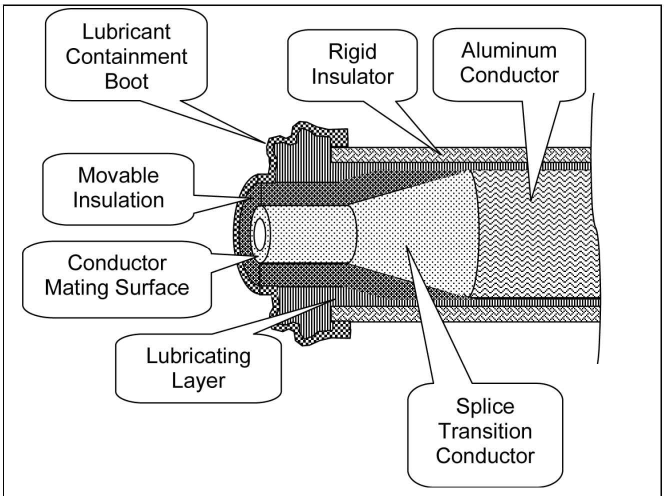


Figure 4: Rigid Insulation for Elpipe Segment
This shows the end of an elpipe segment module. Rigid insulation in the shape of a pipe surrounds the inner conductor, but is only attached to the conductor at one ring (not shown). The thermal expansion can be different between the insulation and conductor in this design. An end-cap of bonded movable insulation covers the splice transition conductor, and can slide within the rigid pipe-shaped insulator along with the conductive core. An elastomeric boot seals between the outer rigid insulator and the inner, movable insulator and holds in the high dielectric strength grease that fills the voids between the moving parts.

2.3 Thermal Expansion of Elpipe**s**

A side effect of going to rigid conductors as in an elpipe is that one must deal with the different thermal expansivities of the conductor, the insulator, the conduit shell, and the Earth. The design of Figure 4, by allowing independent expansion

of the conductor and insulator, takes care of one problem relating to thermal expansion, the mismatch of expansivity of bonded polymeric insulation to the metal conductor. One still has the problem of expansion and contraction of the conductor and the conduit to deal with, however. Various prior art means to deal with thermal expansion of rigid elpipe components include:

- Bellows-type expansion joints (can be used on both conductors and the conduit);
- Sliding electrical contacts have been used for rigid conductors in gas insulated lines [10]; these can limit angular flexibility;
- Using wires within a structural shell that can "snake" as they expand;
- Using flexible conduit pipe that is placed into concrete as it is poured, negating the need for conduit expansion joints.

Each of these methods has deficiencies. It is possible to decouple compensation for linear expansion of the conductor from angular misalignment of neighboring elpipe segments; a linear expansion joint in the middle of each segment module that does not allow angular displacement can be combined with splice modules that only allow angular displacement to produce the needed flexibility.

It is useful to decrease the linear expansivity of the conductor. For example, a 20 meter long aluminum conductor would expand 3.8 cm between 20^o to 100^o Celsius, whereas a pipe made of high purity Invar would only move 1.0 mm, about 3% as much thermal expansion as aluminum. Invar iron/nickel alloy has a thermal expansivity around $1/38^{th}$ that of aluminum.

Invar can be used to "package" sodium so that conductors having the low linear expansivity of Invar can be made. This implies far fewer expansion joints; it is possible that the savings from fewer expansion joints would pay the cost penalty for using Invar. The Invar-encased sodium conductor design has another advantage besides lower thermal expansivity over the aluminum-encased sodium conductor design: in a fire, Invar-encased sodium would be able to withstand much higher fire temperatures without leaking molten sodium to feed the fire.

2.4 Overload Capacity of Elpipes

Because of their massive design, elpipes have high adiabatic overload capacity. In an all-aluminum elpipe design, the adiabatic heating of an elpipe from normal operating conditions (85ºC) to thermal overload (105ºC) would require 2.5 hours at double the normal level of transmitted power, about 15 times as much overload capacity as typical underground cables.

Versions of elpipes that use sodium as the principal conductor have even higher overload capacity due to the endothermic melting of sodium at 98ºC. Indeed, sodium-conductor elpipes can achieve a nearly constant rate of heat shedding, day and night, through storage of heat in molten sodium.

2.5 Cooling Options

Elpipes can be much more massive than cables because they need not be wrapped on a reel for transport. Because of this, elpipes have a "cooling" option that is not feasible for high power cables: one can simply use more conductor to reduce I^2R heat generation in the first place. (As long as the elpipe is DC, there is no dielectric loss also generating heat, as would be the case if AC were used.)

Lower heat generation also means higher efficiency. Although a lower capital cost might be had by using smaller conductors with an active cooling system, higher losses would increase operating costs, and added complexity due to the cooling system would reduce reliability. I therefore favor passively cooled designs wherever that is practical. There are, however, certain cases where structures and/or geology may force an elpipe to go deep under a river or a subway system, for example; in these special cases, an active cooling system will be required.

In a passively cooled elpipe, the electrical insulation is a major part of the thermal resistance between the elpipe conductor and the environment. If the elpipe is at the surface or buried only shallowly, the electrical insulation represents most of the thermal resistance to dumping waste heat into the environment passively, (at voltage > 325kV), whereas at some burial depth (which varies with pipe diameter, voltage and soil type), the soil thermal resistance becomes even greater than that of the electrical insulation material; thus elpipes intended to be deeply buried need a means to bring the waste heat to the surface, such as heat pipes (passive) or liquid coolant pipes (active) as part of the design.

At the typical elpipe design efficiency (1% loss per 1000 km at full rated load), I^2R heat generation is 10 watts/meter per GW capacity, considering both wires (leakage current heating is much less for an XLPE-insulated elpipe than I^2R heat generation). Present generation buried high power cables have thermal limits between 40-70 watts per meter per cable (up to 140 watts/meter for both cables); I have conservatively estimated that a fully buried elpipe circuit (a pair of elpipes as in Figure 1) can dissipate sufficient heat (120 watt/meter) to transport 12 GW at steady state, with large temporary excursions if needed. This particular 12 GW elpipe, with a 40 cm outside conductor diameter, could be buried two meters deep in soil with a minimum thermal conductivity of 1.0 W/mK (a midrange soil conductivity) and still shed its heat to the environment effectively [3].

2.6 HVDC Grid Considerations

So far, commercial HVDC lines are point-to-point linkages, as in Figure 5, with power transformed from AC to DC and back by highly efficient thyristor-based line commutated converter (LCC) stations. LCCs require highly coordinated control of power in/ out for each converter, and as a result, most experts do not think that more than six power taps are reliably operable on multi-terminal LCC-based HVDC lines.

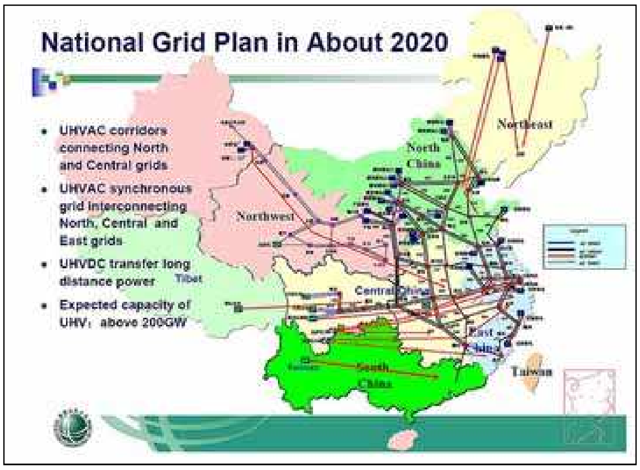


Figure 5: Present Plans for China Grid Expansion
This shows one version of a future Chinese Grid [16]. The basic morphology of the transmission lines comprises point-to-point, or multi-tap lines. Loops do occur, but more as an afterthought than as a basis for planning.

LCCs also do not have "black start" capability, so the lines can only be restarted once the AC grid is operational in the case of a major blackout. More recently, two types of "voltage source converters" (VSC) have been commercialized for power transmission: GTO (gate turn-off thyristor) and IGBT (integrated gate bipolar transistor). VSCs are much more capable of being deployed in a true HVDC grid (with hundreds of power taps) than are LCCs (though this is not yet demonstrated at grid scale).

Unfortunately, VSCs are less efficient than LCCs, and are at present limited to lower voltage (325kV vs. 800kV). Currently, two IGBTs would have ~3% conversion loss versus ~1.2% loss for a pair of thyristor-based LCCs. A recent patent application based on cold cathode vacuum tube switches claims to be a breakthrough in high efficiency, high voltage VSCs [11]. A mixed grid, with both VSC and LCC converters, is feasible and is a likely design for the HVDC grid of the future; such a grid will be capable of having more power taps than a purely LCC-based grid because of the presence of VSCs in the grid, yet the bulk of power transfers can occur through the more efficient LCCs.

Figure 6 illustrates a version of a Chinese supergrid based on interlocking elpipe loops that extend into Siberia, India, and Pakistan (eventually to Europe and Africa). The high redundancy that is intrinsic in this design compared to alternative designs with major trunk lines is very desirable for maintaining reliable power supply in the face of losing one or even two major lines simultaneously.

The terminations in Siberia of Figure 6 would tie into HVDC pipelines following the Trans-Siberian Railroad (Figure 7), which would allow power sharing with Russia and ultimately with Europe. Installing any kind of DC electric pipeline, whether it is an elpipe, GIL, HTS, or some new high capacity overhead line, would be easier to accomplish by following the right-of-way of the Trans-Siberian Railway.

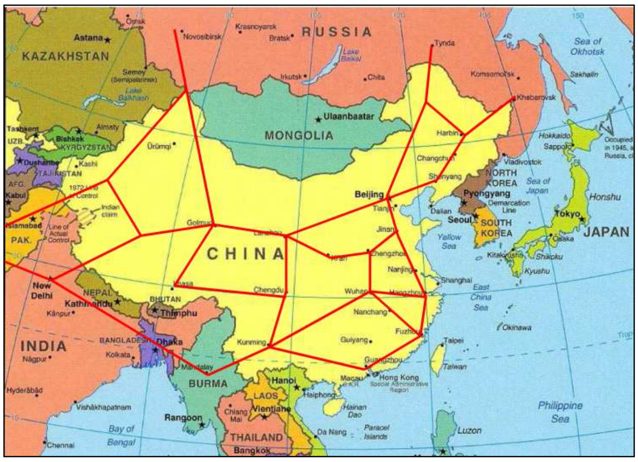


Figure 6: Proposed HVDC Grid for Continental Asia *Connections to Europe via HVDC lines along the Trans-Siberian Railway (Figure 7) and on to Africa (routes not shown in meaningful detail; meant to illustrate the concept).*

The implied southern elpipe route to Africa of Figure 6 would tie the Asian Grid to North African solar, and the immense potential pumped storage capacity of Africa. The Southern route could potentially follow the "Orient Express" rail line, or the proposed route of a gas pipeline from Iran to China. I do not mean the specific route plan I have presented in Figure 6 to be seen as any kind of political statement; logically, Japan, Indonesia, The Philippines, Southeast Asia and Southern India should also be part of an Asian grid.

Figure 7: Trans-Siberian Railway Route

Loops efficiently provide redundancy, which is critical to create a reliable grid. A recent EPRI patent [17] describes use of an HVDC multi-terminal loop around a metropolitan area, to reinforce the grid and protect a region from a propagating blackout due to a remote disturbance that affects a major feeder line. The main circuits of Figure 6 are based on pairs of elpipes, or even multiple parallel circuits. Many smaller lines would also be deployed (not shown in Figure 6). These smaller lines could include elpipes, GIL, HTS, underground cables, and/or overhead lines.

2.7 Installation Options

Elpipes can be installed in several different ways. In principle, a bipolar circuit can be installed in a single pipe, for example. I have rejected this option due to the likelihood that a short in one conductor will damage the insulation of the other conductor, so that both legs fail at once. Having both conductors in a single conduit also means that during maintenance both legs of the circuit will have to be shut down. I think that separate conduits are desirable because of the flexibility offered by this approach. Close spacing of the conductors minimizes inductance and local magnetic effects (inductive energy must be dissipated or stored to open the circuit).

In a loop system, the total resistance between two points R_{total} is related to the clockwise resistance R_1 and the counterclockwise resistance R_2 by:

$$R_{total} = 1/(1/R_1 + 1/R_2)$$

The maximum point-to-point resistance occurs when $R_1 = R_2$. Loops provide intrinsic redundancy provided there are "hot" circuit breakers between each pair of next neighbor taps on the HVDC loop. However, such hot HVDC circuit breakers still need further development, and will likely be expensive. Fast-acting HVDC circuit breakers [12] are especially expensive. Combining a few fast-acting breakers with a large number of slow-acting (~100 ms) but less expensive circuit breakers [6], plus many zero-load switches, is a likely scenario for circuit protection. In the event of an outage, the portion of such a grid that lies between hot circuit breakers can be rapidly reconfigured using zero-load switches to allow each node point to be serviced from at least one loop direction (by isolating the fault via opening zero-load switches). After this reconfiguration, the VSC converters can do a cold start. Not all the converters, however, have to be VSCs (as discussed above).

To minimize magnetic fields near an elpipe, it would be highly desirable to have a coaxial relationship of the + and – conductors. This is indeed feasible for monopole systems with return current near ground potential. It is true in principle that a ±800kV system could be replaced by a +1.6MV monopole system with near ground potential return through the coaxial shell, and carry the same power for the same amount of invested conductor, with esentially zero magnetic effects. This design would complicate field repairs, expansion joints, and cooling, and is not favored for now but remains a possibility in the future.

For added redundancy, it is desirable to deploy bipolar elpipes with an emergency ground return elpipe (which does not require high voltage insulation). In this scenario, either "hot" elpipe can be taken out of service, and the remaining line + the ground return spare will still be able to deliver full load for a time (the overload time), and half load thereafter. However, this is expensive compared to ground return; it is my opinion that DC ground return should be allowed in emergencies for however long it takes to fix the lines.

Elpipes have a minimum radius of curvature (without using special elbow joints) that is smaller than a welded gas pipeline but larger than an HVDC cable. Elpipe minimum radius of curvature lines up well with the minimum radius of curvature of railroads and high speed, limited access highways. HVDC lines could be conveniently installed underground next to gas pipelines, railway lines, or interstate highways. Construction along railroads is especially appealing because long segments of jointless elpipe can be rail transported. Even if the segment length can only be extended to the length of two rail cars, this would imply one-fourth as many splices as will be required if the elpipe segments must be transported over roads. The resultant savings would be significant, and in principle even longer pieces of elpipe, corresponding to the length of an entire train (~ one kilometer), could be rail transported to the trench. This is relatively less important if the elpipe is assembled at one end and rolled into the conduit, which is my favored method of installation at present.

Figure 8 depicts an installation and maintenance vault. I envision such vaults being around 10-20 km apart. During construction, the elpipe segment modules could be coupled with the splice modules in a highly controlled environment inside such vaults, then rolled into the conduits. Alternatively, there could be only one assembly area for the elpipes on any given line; this is most desirable from the point of view of strict quality control. The fewer the number of assembly points, the more cost-effective it is to deploy advanced sensors (like x-ray tomography and ultrasonic inspection of each joint) and expensive testing methods at the point of assembly.

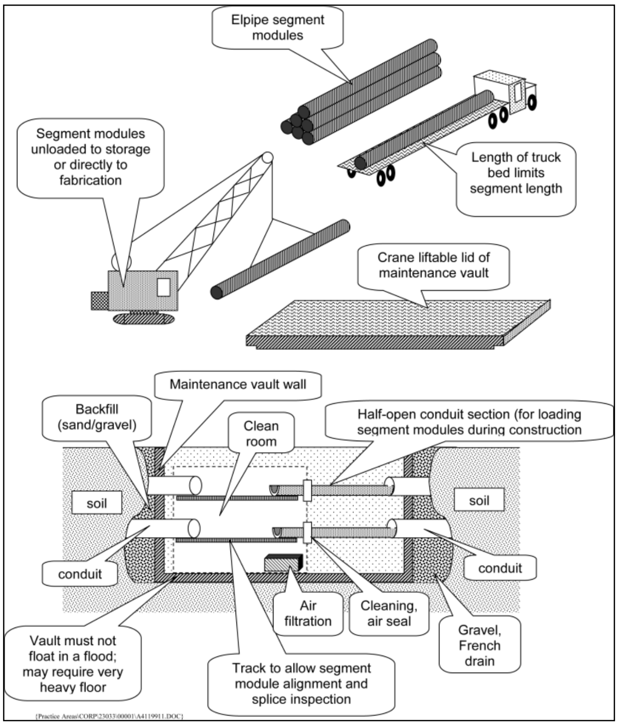


Figure 8: Installation and Maintenance Vaults

2.8 Maintenance & Repair of Elpipes

Repair of an underground line typically takes much longer than an overhead line if it has to be dug up. Most HVDC cables are buried directly, rather than in a conduit. Average time to repair a ground fault in a buried underground line is around 160 hours, compared to about 4 hours for a similar fault in an overhead line.

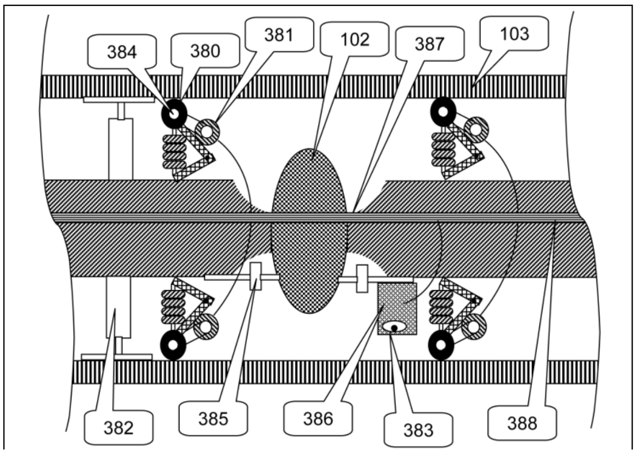


Figure 9: Splice Module and Carriage Details

Two segment modules are linked through one splice module [102]. Wheels [380] are connected to torque sensing means [384] and to a reversible variable speed and variable torque motor [381]. A load cell [385] senses axial load between each segment module and splice module that are connected. There is a parking brake [382], on only one side of the splice module. Power for the motor drives is supplied by a cable [388] which supplies both power and an intranet connection between the local control module [386] and the control room for the elpipe. An inclinometer [383], the torque sensors [384], and the load cells [385] all feed their information to the controller [386] which controls the drive motors [381] so as to engage in coordinated and controlled movement of the "elpipe train" while minimizing stress on the splice module.

My elpipe design is capable of rapid repair because the entire elpipe is a single long train. Neighboring segment modules are linked together through a splice module, as in Figure 9. The ends of each segment module are supported by wheels, which are powered and held against the conduit inside wall by springs. There is a parking brake that is engaged when the elpipe is stationary (most of the time). During insertion of the elpipe into the conduit, or withdrawal from it, the wheels are powered and controlled similarly to model trains. Not all wheels need to be powered, but in regions where the elpipe must climb and descend mountains, it is likely that most sets of wheels will be driven (to avoid excess stress on the elastomeric splice modules).

The train-like nature of a wheeled and powered elpipe can be used to enable rapid repairs of most faults, as well as for routine maintenance, inspection, and upgrading of power transfer capacity. Figure 10 shows how only a few sidetracks are needed to enable rapid repairs of such a system. A sidetrack could enable an elpipe section that has been damaged hundreds of kilometers away from the nearest sidetrack to be moved into a maintenance vault because the entire elpipe "train" is backed into the siding until the fault is located in a maintenance vault. (This requires that the train be decoupled in the sidetrack switchyard.)

3 Importance of Load Balancing for Wind & Solar

It is essential to provide balancing resources for wind and photovoltaic-based solar (concentrating solar with molten salt storage is dispatchable, and so does not require balancing). One needs a dispatchable capacity that is equal to the wind capacity if the wind energy from a single site is to be included in the capacity base. This requirement loosens a bit when different geographical areas are tied together on a single grid, since the reliability of geographically distinct sites increases with the number of distinct wind sites included in the average. This is a great advantage of an HVDC grid such as in Figure 6 over linear point-to-point lines as in Figure 5.

To levelize energy availability from wind it is highly desirable to have an HVDC grid with enough capacity to tie together an entire region, rather than merely connecting two to six AC/DC converters along a linear HVDC line [13]. It has been shown [14] that even at the current level of wind power generation in the US, the existing electrical grid contains bottlenecks that result in curtailment of wind energy production, as is also occurring in China. Mixing wind and solar together on a single large grid reduces variability further, because cloud cover often correlates with greater wind power availability. The HVDC grid of Figure 6 would not only relieve the bottlenecks, but would improve the aggregate reliability of wind + solar by spreading the capacity over many geographical regions, with different weather patterns. Geographical smoothing is far less effective with the point-to-point lines of Figure 5.

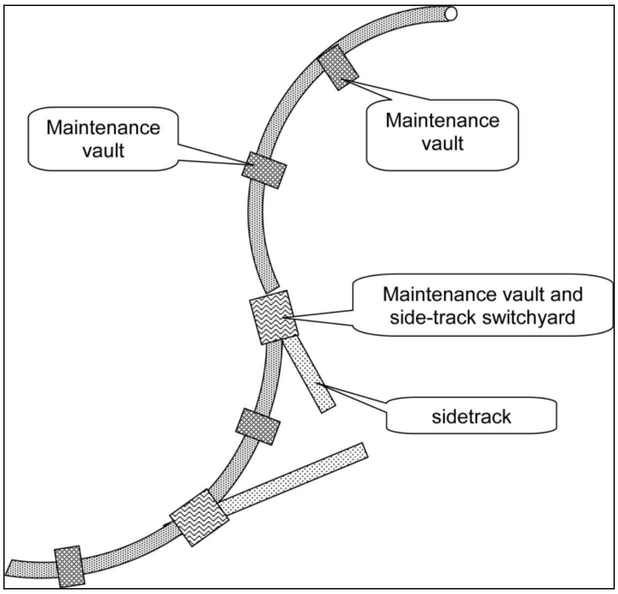


Figure 10: Long Elpipes Showing Rapid Repair Strategy

A strongly connected Eurasian DC supergrid would enable sharing wind, hydro, solar, and pumped storage resources over a vast area. Compared to any other contiguous land mass on Earth, Eurasia + Africa has the greatest area, the best resources, and the greatest population of anywhere on Earth. This highly interconnected super-continental scenario is hinted at in Figure 6. The great geographical reach of such a supergrid would tie in 14 time zones of wind and 10 time zones of solar energy together with a large dispatchable hydro and pumped storage capacity. Such a supergrid would reliably aggregate output of wind and solar from a huge area. The grid must have dispatchable capacity to level the load, and an HVDC supergrid enables non-local pumped storage and dispatched hydro to provide load balancing at much lower cost than batteries and flywheels [18].

Another way in which a strong HVDC grid enables higher penetration by wind and solar power is that it enables more effective use of existing pumped storage facilities, and enables new dispatchable hydro and/or pumped storage facilities that are far away from population centers (Siberia is particularly relevant in the Asian context with regard to hydropower facilities, both dispatchable hydro and pumped storage).

4 Siting, Installation & Right of Way

The cost of burial of an elpipe mainly scales with the local ground conditions, the volume of earth removed to make the trench, and the number of parallel trenches. Getting both poles in one trench is desirable in terms of installation cost, and putting the two conductors close also minimizes transmission line inductance; lower inductance means less stored energy that must be dissipated during opening of transmission line circuit breakers [6]. Closer spacing of the lines also narrows the ROW (right of way), and reduces the local perturbation of the earth's magnetic field. Deep burial is desirable from a security point of view, and can be implemented with heat transfer to the surface via passive heat pipes. Placing the two pipes on top of each other will reduce the surface magnetic perturbation; however repairs would be easier with side-by-side placement.

5 Installed Cost of Elpipes

The ground-up calculated cost of three different size bipolar HVDC elpipes (3, 6, 24 GW) in the US were presented to a meeting of the IEEE Power and Energy Society [18]; an excerpt from that paper shows the major elpipe component costs (Table 1). Table 1 shows all costs except right-of-way purchase cost. Raw materials represent 36% to 39% of the total cost of all three 1600 km transmission lines, with AC/DC converters representing 15% of the cost for the smallest (3 GW) elpipe, which climbs to 40% of the total cost for the 24 GW design. The assumed two-way cost for the AC/DC converters used in Table 1 was $229/kW. (I got this cost number from a US ISO transmission planner in 2010; this cost would be reduced greatly if China built an 800kV supergrid, thus reducing the cost of a vital supergrid component for all nations. Such a step is comparable to the way China has made solar cells more affordable worldwide.)

In the case of the multi-terminal HVDC loops that I am advocating, the total installed AC/DC converter capacity attached to a loop must be higher than that of Table 1, which models the conventional point-to-point type of HVDC connection. It is obvious that for the DC supergrid to reach the state of development of Figure 6, lower cost converters will be very important.

Table 1: Cost per km of Three Sizes of Elpipes

Capacity Voltage	3 GW ±500 kVDC	6 GW ±800 kVDC	24 GW ±800 kVDC
Current	3,000 A	3,750 A	15,000 A
Loss (2-way, hot)	1.00%/1000km	1.00%/1000km	1.00%/1000km
Heating (2-way)	30 W/m	60 W/m	240 W/m
Resistance (each conductor, hot)	1.67E-06 Ω/m	2.13E-06 Ω/m	5.33E-07 Ω/m
Aluminum cost (2-way)	$467k/km	$365k/km	$1461k/km
XLPE cost (2-way)	$199k/km	$462k/km	$569k/km
Trundle cost (2-way)	$17k/km	$17k/km	$0/km
Steel cost (2-way)	$165k /km	$306ki/km	$439k/km
Braid cost (2-way)	$25k/km	$198k/km	$791k/km
Silicone rubber cost (2-way)	$375k/km	$871k/km	$1072k/km
Bellows cost (2-way)	$252k/km	$350k/km	$403k/km
Concrete cost (2-way)	$0/km	$0/km	$137k/km
Total Raw material costs	**$1.73M/km**	**$2,57M/km**	**$4,87M/km**
Fabrication cost	25%	25%	25%
Cost Of Goods	$2.2M/km	$3.2M/km	$6.1M/km
Gross margin	35%	35%	35%
Sell price	**$3.3M/km**	**$4.9M/km**	**$9.4M/km**
Installation cost	$780k/km	$780k/km	$780k/km
Installed cost (no converters)	**$4.125M/km**	**$5.75M/km**	**$10.19M/km**
Transmission line $/kW-km	$1.38	$0.96	$0.43
Line length	1600 km	1600 km	1600 km
Converter station cost (2-way)	$229/kW	$229/kW	$229/kW
End-to-end cost	**$4.5M/km**	**$6.6M/km**	**$13.6M/km**
Total cost/kW-km	**$1.51**	**$1.10**	**$0.56**

6 CONCLUSIONS

The proposed system represents a paradigm shift for power transmission in several ways. First is the obvious movement from wires to solid conductors, "electric pipelines." This is an unavoidable consequence of the need for increased power transfer.

Elpipes are one of only three feasible alternatives for building continental scale HVDC grids, the others being superconductors [15] and GIL [10]. I believe the HVDC grid of the future will probably include superconducting segments, GIL, cables, overhead lines, and elpipes, all operating at a single voltage between 500-800 kV.

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Roger W. Faulkner was born in Ravenna, Ohio (USA) in 1954. He received a B.Sc. degree from Akron University (Chemistry & Chemical Engineering) in 1980. He studied for the Ph.D. in Polymer Science at Akron University from 1981-84, where his research was on reactive polymer processing. Since then he held a variety of jobs, mostly developing polymeric products including tires, adhesives, coatings, thermoplastic elastomers, plastics compounds, and new rubber chemicals and graft polymers. He also has been politically active in pursuit of environmentally sound technology and resource policy. In 2009 he turned his long standing interest in a DC supergrid (as a key enabler for renewable and carbon-free energy) into a startup company, Electric Pipeline Corporation.

Tel: 617-549-9492 (USA)

E-mail: roger.faulkner@elpipe.com