Massive Underground HVDC Transmission via Elpipes: Implications for Grid Evolution

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Abstract— *Elpipes are polymer-insulated underground HVDC power lines that use relatively rigid extruded conductors designed for higher capacity and efficiency than is practical for overhead power lines. Elpipes can use far more conductor than cables, but also have more splices that an HVDC cable. The high efficiency of elpipes is motivated by the need to minimize heat dissipation while maintaining passive cooling. Minimizing waste heat production is critical since heat dissipation limits capacity. For a 325-800kV DC elpipe, we have selected a design basis of 1% loss per 1000 km, about three times better than an overhead 800kVDC line, and similar to "high temperature" superconducting (HTS) lines after accounting for the energy HTS lines consume for cryogenic cooling. This high efficiency could enable continental scale power transfers with acceptable loss, using fully buried aluminum elpipes carrying up to 12 GW. Surface mounted elpipes can deliver power up to at least 24 GW, whereas with internal cooling transfer capacities up to 200 GW are feasible.*

1. INTRODUCTION

Elpipes are composed of solid-insulated pipe systems (Figure 1) which can be fully underground, installed at the surface (Figure 2), or above ground. Figure 1 illustrates a simple design with aluminum conductor, insulated by crosslinked polyethylene (XLPE), within a steel conduit. This 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 at this time.

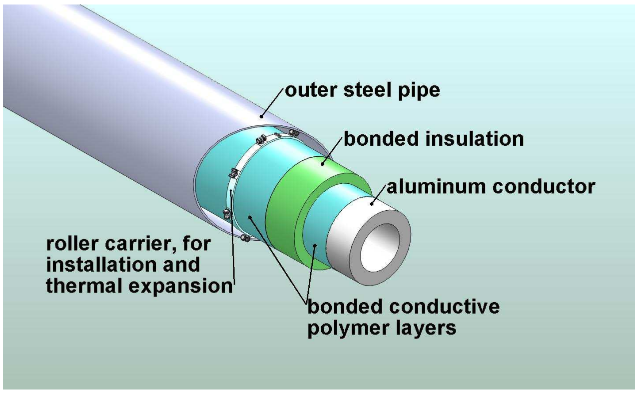

Figure 1: Buried HVDC Elpipe

An elpipe installed at the surface (Figure 2), could go to at least 24 GW with passive cooling. Active, non-cryogenically cooled elpipe designs can theoretically go to transfer capacities above 200 GW. Note though, that such high capacities would require full redundancy to meet North American reliability standards, and (like any HVDC grid, including both overhead lines and HTS cables) would require new HVDC circuit breaker technologies that are yet to be developed and proven.

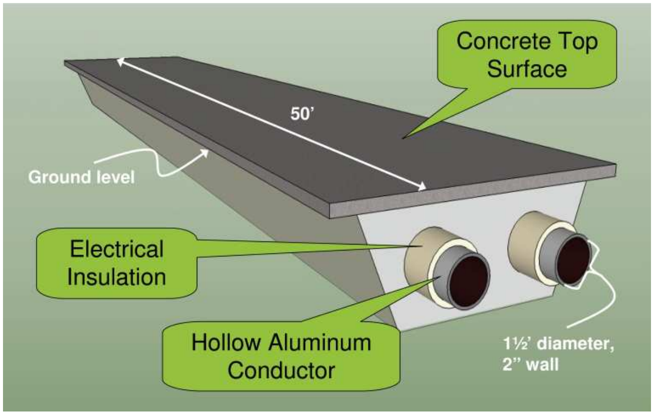

Figure 2: Surface-mounted HVDC Elpipe

We examine in this paper how elpipes could fit into an HVDC grid that also incorporates other technologies such as overhead HVDC, gas insulated lines (GIL), flexible cables, and HTS superconducting cables. It is highly desirable to devise an HVDC grid around a single operational voltage, since DC/DC transformers are quite expensive.

Elpipes and HTS cables could form a highly redundant HVDC supergrid in North America [1], as in Figure 3. The idea of long distance underground HVDC transmission in North America was considered as a possibility as early as 1983 [2], but the technology that would truly enable an HVDC grid has only recently become available. Another publication by the authors [3] discusses design voltage, insulation, thermal management, installation options, and trade-offs on conductor selection for elpipes. In this paper we take as a given an aluminum conductor, crosslinked polyethylene (XLPE) insulated elpipe, and operating voltage of 800kV, corresponding to the highest proven operational DC voltage, deployed recently in two overhead lines in China [4].

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Of the HVDC technologies that are either proven or under development, only overhead HVDC is in service at 800kV at present, but it is clear that there is a need for a standardized HVDC voltage that is between 500-800kV. This paper adopts 800kV as a common operational voltage as a basis for comparing the alternatives in this paper. HTS cables have the furthest to go to demonstrate operability at 800kV DC among the various long distance HVDC options (GIL, elpipes, cables, HTS). For the purpose of this comparison, we do not consider the engineering hurdles in detail for each technology. (Cables have been deployed at 500 kVDC and tested at up to 600 kVDC [5] while GIL has not been used in HVDC transmission as of yet.)

Figure 3: North American HVDC Hybrid Grid Concept (red lines are elpipes, blue lines are 800kV HTS lines)

2. ELPIPE'S ROLE IN HVDC GRID OF THE FUTURE

Unlike a purely superconductor-based coast-to-coast supergrid, if either or both of the superconducting links of the grid is lost in the proposed hybrid grid of Figure 3, there is enough capacity in the elpipe portion 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 a coast-to-coast link is broken in a purely superconducting grid. Such a hybrid grid could allow lower reliability for the HTS links.

As long as the abrupt change in delivered power remains within safe limits, loss of either or both of the superconducting lines of Figure 3 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 provide redundancy to the elpipe based supergrid, while increasing transfer efficiency, and moving most of the east-west flow. The presence of conventional elpipes would allow the many HVDC/AC power taps and feeder lines (HVDC overhead lines, cables, etc.) to be attached to the conventional elpipe rather than to a superconducting cryogenic HTS line. This will help reliability, because the superconductor/ohmic conductor interfaces are especially problematic, both in terms of efficiency and reliability. The elpipes would also improve system stability by damping potentially destructive resonances that are hard to deal with in a purely superconducting grid.

Such a hybrid design (Figure 3) 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 the 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 demonstrated 200kV to the 800kV level that makes the most sense for a conventional-conductor based HVDC grid.

The grid concept of Figure 3 requires numerous technical breakthroughs before it will be possible; however there is a significant need to improve the ability to share power regionally. It is increasingly difficult to site overhead lines, which means there is a strong need for an underground option capable of transporting > 5 GW. There have been various consensus design processes (JCSP [6]; EWITS [7]) aimed at bringing US Midwestern wind power to the East coast; all rely extensively on overhead HVDC lines; see Figure 4 for example.

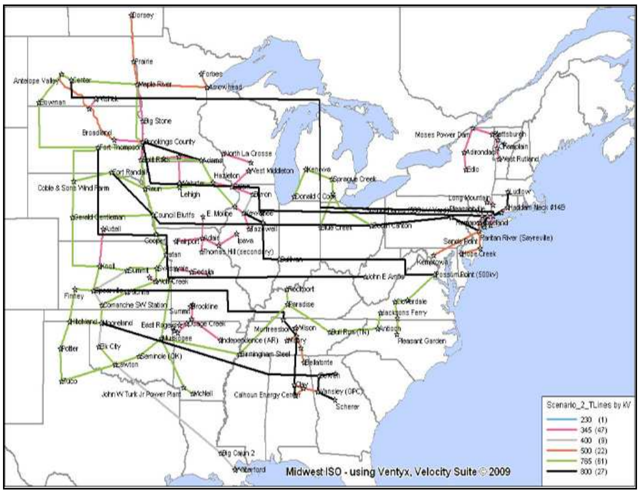

Figure 4: EWITS [7] Scenario 2, Proposed HVDC Lines

So far, commercial HVDC lines are point-to-point linkages, as in Figure 4, 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/power out for each converter station, and as a result, most experts do not think that more than six power taps are reliably operable on lines such as those shown in Figure 4.

Contrast this with the true HVDC network envisioned in Figure 5, which can move power from any power tap to any other tap; there would be on the order of 50-100 power taps on the HVDC loop of Figure 5, which would tie together an area with hundreds of GW of power production and consumption. The proposed HVDC grid would reinforce the three conventional AC synchronous grids in the region. Figure 5 shows the highest capacity elpipe circuits as heavy lines, but a realistic HVDC grid would also contain smaller underground cables, and/or overhead lines.

A true HVDC grid (with more than six power taps) cannot be built based solely on LCCs. 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 (~3% conversion loss for two IGBTs vs. ~1.2% loss for a pair of thyristor-based LCCs; GTOs are intermediate in efficiency). A mixed grid, with both VSC converters and current source converters is feasible and will be 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 occur through the more efficient LCCs.

Figure 5: HVDC Grid for Eastern US

Loops efficiently provide redundancy, which is critical to create a reliable grid. An HVDC grid such as that of Figure 5 would lie “below” the conventional AC synchronous grids (three synchronous AC areas are linked by the HVDC grid of Figure 5), and would reinforce them. The main circuits of Figure 5 are based on pairs of elpipes as in Figure 2. The Main Loop circuits can also be connected to smaller HVDC elpipes, underground cables, and/or overhead lines carrying 1-7 GW (a few are shown in Figure 5).

Ideally, such an HVDC grid would be tied into the regional AC grids at many points, but there are serious control issues with an HVDC grid that limit the maximum number of “taps.” This is an issue of keen interest to several research groups [8].

3. ELPIPES VERSUS SUPERCONDUCTING CABLES

Elpipes have a resistive I^2R loss that HTS cables do not have; this loss increases with the square of power transmission. Our design basis standard for elpipes is to set I^2R loss at 1% of transmitted power per 1000 km at full rated power (this implies using 3-18 times as much conductor as would be used in a conventional HVDC power transmission line). If an elpipe transmits less than its rated power, efficiency improves (up to a point; eventually at very low transmitted power, leakage flow comes to dominate transmission loss, and efficiency falls).

This behavior is very different than for an HTS cable, for which the major energy loss along the cable length is the energy input for cooling. (The cooling energy required at the superconductor/ohmic conductor junctions does scale with transmitted power, however.) To a first approximation, energy cost of cryogenic cooling does not vary with transmitted power; as a result the efficiency of an HTS cable is maximal just below the maximum power transmission level (100% of rated power), and decreases at lower transmitted power levels. Contrast this with elpipes, for which the design basis efficiency of 1% I^2R loss per 1000 km at full rated power is about the same as cryogenic cooling energy cost of an HTS line at 100% of rated power [9], this implies that at less than rated power, elpipes will be more efficient.

Efficiency per se is not a major difference between elpipes and HTS cables. A far more important issue is reliability; for an HTS system to work, it must be cryogenically cooled at all times. This implies increased operation cost (energy cost of power used for cooling), and increased maintenance cost (to operate and maintain the required quadruple-redundant cryo-coolers needed to guarantee that the superconductor does not rise above its critical temperature).

Another significant difference between HTS cables and elpipes is the behavior of these cables when overloaded for brief periods. An HTS cable has a well-defined maximum ampacity; if even a little more current flows than this maximum, the superconductivity (which is a quantum process) is quenched, which would lead to a catastrophic failure. Elpipes on the other hand are very tolerant of temporary overloading beyond their design ampacity. As an example, a typical aluminum/XLPE elpipe can carry twice its rated load for 2.5 hours before the insulation is heated from normal peak operating conditions (85ºC) to thermal overload (105ºC). Much larger power excursions can be tolerated for shorter lengths of time. Versions of elpipes that use sodium as the conductor have even higher overload capacity due to the endothermic melting of sodium at 98º Celsius. (See reference [3] for a comparison of different conductors for elpipes.)

4. ELPIPES VERSUS GAS INSULATED LINES (GIL)

GIL has been around for 35 years, and is commonly used for short runs between the generator/step-up transformer and the switchyard. Although GIL has been proposed for HVDC transmission [10] all the commercial installations of GIL (the longest of which is less than 5 km) have been for AC power transmission [11], where the low capacitance of the line compared to a cable allows for much longer runs of AC power underground than is feasible for cables.

5. ELPIPES VERSUS OVERHEAD HVDC LINES

As mentioned previously, the design basis efficiency standard for HVDC elpipes is 1% I^2R loss of transmitted power per 1000 km at full rated power. This compares to published efficiencies for the two recent 800kV DC powerlines in China of 2%/1000 km at 5 GW for the Siemens Project [12], and <3%/1000 km at 7.2 GW for the ABB project [13].

The two to three times higher efficiency of elpipes compared to overhead power lines is motivated more by the need to minimize waste heat production to make passive waste heat removal possible than it is to make efficiency very high. The extra efficiency versus 800kV overhead becomes significant economically when one goes to true continental scale grids (>2000 km transmission), but elpipes still have major advantages over overhead power lines on shorter runs in some circumstances; for example where capacity > 7 GW is needed, or where overhead lines cannot be permitted, but an underground option can be permitted.

6. ELPIPES VERSUS CONVENTIONAL CABLES

Elpipes can be much more massive than cables because they need not be wrapped on a reel for transport. In a sense, 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.) High voltage cables that are truck-transportable can use no more than 2.5 cubic meters of conductive metal per km, whereas electric pipelines can easily use ten times as much conductor, or more. 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. We therefore favor passively cooled designs wherever that is practical. (This creates a potential windfall for large producers of aluminum; in a normal overhead transmission project, the aluminum acquisition cost is on the order of 1% of total project cost, whereas for an elpipe, aluminum per se typically amounts to 10-20% of project cost.)

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 (but not cryogenic) cooling system will be required.

In a passively cooled high voltage elpipe or cable, the electrical insulation is a major part of the “thermal resistance” between the elpipe conductor and the environment. Recent developments with HVDC polymeric insulation [14] are expected to lead to thinner polymeric insulating layers on HVDC cables, which may boost maximum capacity and voltage of XLPE-insulated cables to around 2-3 GW at 800kV, still far short of what can be achieved with overhead power lines or elpipes.

If the elpipe is at the surface (as in Figure 2), or buried only shallowly, the electrical insulation represents most of the thermal resistance to dumping waste heat into the environment passively (at voltage > 325 kV), whereas at some burial depth (that varies with pipe diameter and soil type), the soil thermal resistance becomes even greater than that of the electrical insulation material; thus elpipes cannot be deeply buried unless a means to bring the waste heat to the surface, such as heat pipes (passive) or liquid coolant pipes (active) are 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); we have conservatively estimated that a fully buried elpipe circuit (a pair of elpipes, each as in Figure 1) can dissipate sufficient heat to transport 12 GW at steady state (120 watts/meter), with large temporary excursions if needed.

As mentioned above, because of their massive design, elpipes have high adiabatic overload capacity. Elpipes offer about 15 times as much overload capacity as typical underground cables.

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. We have rejected this option due to the likelihood that a short in one conductor would 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 would have to be shut down. Thus, we think that separate conduits are desirable.

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 [15] between each pair of next neighbor taps on the HVDC loop. However, such hot HVDC circuit breakers still need to be developed for the power levels envisioned for an HVDC loop as in Figure 5, and will likely be very expensive, so a fewer number of hot HVDC circuit breakers, combined with many more fast acting 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 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 IGBT-based converters can do a cold start.

To minimize magnetic effects 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. Monopole systems use the conductive material less efficiently than bipole systems in one way of looking at it (same mass of conductor as a bipole with half the voltage). Routine use of the conduit for a moderate voltage (near ground potential) return current would complicate field repairs, expansion joints, and cooling tremendously, and is not favored for now (this remains a possibility in the future).

National Electrical Safety Code (NESC) only allows 30 minutes of emergency operation of one leg of an HVDC system with ground return [16]. For added redundancy, it would be desirable for the bipolar elpipe to default to an effective monopolar design in case of a fault in one pole. We are at present pursuing designs (Figures 1 & 2) in which each conductor resides in its own shielding conduit, which may be either metallic or a polymer-based pipe. Making the outer conduit out of aluminum or aluminum/polymer composites would result in the potential for each pole of the HVDC circuit to default to monopolar operation with ground return through its own conduit in case of an outage on one pole. However, it is more economical to install a separate low voltage elpipe specifically designed for ground return in case of an outage in one pole; this has the advantage that the single ground return backup serves both poles of the normally bipolar HVDC elpipe connection. This is somewhat related to the concept of repurposing three-phase AC powerlines to HVDC with a spare pole [17].

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 seamless 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 would 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.

In some parts of the world, major new railroads and gas pipelines are being contemplated; for example the proposed natural gas pipeline [18] that will connect from Iran to China through both Pakistan and India, or the ultimate Maghreb objective of a railway connecting Libya to Morocco and continuing to Mauritania [19]. A strong redundant elpipe connection from Saudi Arabia to Western Europe would likely lead to the development of solar energy and wind energy resources in Saudi Arabia. Saudi Arabia is well situated to develop mega-scale solar electric power generation for export into Europe during the AM peak period, if only there were a way to export the power.

8. GRID STABILITY & STORAGE IMPLICATIONS

Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS) has become an important need in grid evolution, especially in view of the rapid expansion of wind power [20]. It is essential to provide balancing resources for wind; one needs a dispatchable capacity that is equal to the wind capacity if the wind 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 probability of all wind generators at geographically distinct sites being simultaneously shut down decreases with the number of distinct wind sites included in the average.

A North American Grid, such as that of Figure 3 would enable sharing wind resources over several major wind hotspot areas (East Coast, West Coast, Great Plains, Rockies, Great Lakes, Hudson's Bay, for example). It has been shown [21] that at the current level of wind power generation the existing electrical grid contains bottlenecks that result in curtailment of wind energy production. The grid of Figure 3 would not only relieve the bottlenecks causing curtailment, but would improve the aggregate reliability of wind by spreading the risk over many geographical regions, with different weather patterns.

Even if all the wind hotspots in North America were developed, the wind output would vary on a time scale of about 3 week periods. There is only one feasible energy storage scheme in North America that could deal with this "wind energy remainder problem," Niagara Pumped Storage [22]; a +10 to -14 GW swing can be supplied that has enough capacity (1300 GW-hours) to address the three week aggregated variability of North American wind power. However, storage per se is not the only way to supply GRIDS capacity; one must also consider load dispatch.

Table 1 lists potentially dispatchable electrical loads that could be used to supply GRIDS capacity. Adding extra capacity so that an industrial facility that consumes a lot of electrical energy can be dispatched rather than operate 24/7 as is normally the case for electrochemical production facilities deserves to be considered as an alternative way to achieve load balancing and regulation to allow wind power to become a reliable resource. To take a concrete example, if building extra capacity at an air liquefaction site would allow the site to produce the same amount of product using off-peak power only, this is in a sense equivalent to building energy storage capacity per se for load leveling and balancing. Actually, making large loads dispatchable is more desirable from an energy efficiency point of view, because unlike the case for energy storage, there is no round trip efficiency issue: the energy is never actually stored.

Table 1: Industrial Loads that can Balance Wind [23]

Load type	Total U.S. load (GW)
Air liquefaction	1.0
Electric furnaces	1.0
Electrolysis (total)	>14
Aluminum smelting	6.5
Chlor-alkali	4.5
Potassium hydroxide	1.0

Making Industrial facilities such as those of Table 1 dispatchable presents numerous engineering challenges. Each process has its own time constant; for example, electrolysis can do fast regulation but air liquefaction is much slower ramping (response rate similar to a gas turbine). In the case of electrolysis, it is probable that the cells would have to be redesigned to some degree. This is an especially difficult problem for aluminum smelters, which would have to be maintained at ~950^o C even while not electrolyzing material. On the other hand, aluminum smelting represents the largest piece of electrolysis load, and even if the smelter output is varied only a little, aluminum smelters could supply a lot of fast regulation at low cost compared to batteries or flywheels. The essential problem is a lack of transmission capacity to the remote smelters. Aluminum smelters have been built in places like Massena, New York [24], near large hydroelectric projects that do not presently have enough transmission capacity to move the electricity to market. In such cases, a combination of excess smelting capacity (designed for variable output of aluminum) plus new transmission capacity could convert the aluminum plant into a vast resource for load balancing and fast regulation.

Long distance reliable low-loss transmission linking load centers to remote energy storage sites, and to new dispatchable electric loads and generation is an economical way to achieve GRIDS capacity. We propose an HVDC multi-terminal underground system, based at least in part on "elpipes" linking load centers, remote energy storage sites, and non-dispatchable generators (wind, solar, tidal) with a combination of energy storage and dispatchable load resources:

1. Remote pumped storage sites
2. Remote compressed air energy storage (CAES)
3. Fast-responding redesigned electrolysis facilities (aluminum smelters, chlor-alkali plants, and other electrochemical factories)
4. Dispatchable Integrated Gasification Combined Cycle – Carbon Capture and Sequestration (IGCC-CCS)/synfuels facilities) [25]

Such a combined system would create more economical GRIDS capacity than is possible for alternative schemes that store energy locally near load centers.

A particularly interesting dispatchable load is the combination of a synfuels facility with integrated gas turbine combined cycle (IGCC) power plant. The coal mine and gasifier would be running continuously, but the output from the gasifier would swing between synfuels production and power output via the IGCC turbines.

Brian Towler of the University of Wyoming proposed combining the synfuels/IGCC dispatchable supply/demand system with carbon capture and sequestration [26]; the sequestration piece is made much simpler in his concept because the gas turbines operate in a carbon dioxide working fluid rather than a nitrogen working fluid as in air breathing gas turbines [27]. Later professor Towler and Roger Faulkner combined efforts to produce an ARPA-E round 3 application that directly addressed GRIDS storage [25]. Neither of these applications were successful, but preparing these applications aided the evolution of the idea.

9. CONCLUSIONS

The envisioned HVDC grid system represents a paradigm shift for power transmission in several ways. There are many proposals floating around HVDC grids at present; we believe that the HVDC grid of the future will operate at one standard voltage between 500-800kV. The HVDC grid will probably include both LCC and VSC converter stations, and all types of transmission lines. Elpipes will be a favored type for high capacity (>3 GW), low maintenance transmission lines, especially where overhead lines cannot be permitted.

REFERENCES

[1] Faulkner, Roger; Todd, Ronald; Electricity Today, March 2010, “Using conventional Elpipes for Long Distance Transmission”

[2] Mickley, A.S.; Heyer, S.V. of Philadelphia Electric Co.: "Economic and Technical Evaluation of Long Underground DC Transmission," in US DOE Symposium: "Incorporating HVDC Power Transmission into System Planning" (Phoenix, Arizona March 24-27, 1980

[3] Faulkner, Roger; Todd, Ronald; ICHVE 2010 presentation: “Long Distance Underground HVDC Transmsission via Elpipes”

[4] Hong, C.; Yao, X; “The Undergoing and Planned Bulk 800 kV DC Transmission in China”, CIGRÉ SC B4 Meeting and Colloquium, June 6-12 2009, Bergen and Ullensvang, Norway

[5] Marelli, M.; Orini, A.; Miramonit, G.; Pozzati, G.; “Challenges and Achievements for New HVDC Cable Connections”, CIGRÉ SC B4 Meeting and Colloquium, June 6-12 2009, Bergen and Ullensvang, Norway

[6] Joint Coordinated System Plan (JCSP): http://www.jcspstudy.org/

[7] Corbus, D.; Milligan, M.; Ela, E.; Schuerger, M.; Zavadil, B., “Eastern Wind Integration and Transmission Study — Preliminary Findings” September 2009. Pesented at the 8th International Workshop on Large Scale Integration of Wind Power and on Transmission Networks for Offshore Wind Farms, 14-15 October 2009, Bremen, Germany

[8] Consider for example: “Challenges with Multi-Terminal UHVDC Transmissions;” by Lescale, Victor F.; Kumar, Abhay; Juhlin, Lars-Erik; Björklund, Hans; and Nyberg, Krister; Presented at: POWERCON2008 & 2008 IEEE Power India Conference October 12-15, 2008, New Delhi, India

[9] “Superconductor Electricity Pipelines, Carrying Renewable Electricity Across the U.S.A., Out of Sight and Out of Harm’s Way” American Superconductor, May 2009

[10] Ouyang, M.; Carlson, L.E.; and Baker, M.A.; “A ±600 KV HVDC Gas Insulated Transmission Line,” page 167 in The Proceedings of the Symposium in Urban Applications of HVDC Power Transmission, October 24-26, 1983 in Hershey, PA; Conference Sponsored by The Division of Electric Energy Systems, US DOE

[11] Koch, Hermann; “Experience with 2nd generation Gas-Insulated Transmission Lines GIL”; World Energy Transmission System Workshop, Meudon, France, June 2003

[12] “First 800-kV high-voltage direct-current link in China now fully operational”, Siemens press release, June 21, 2010.

[13] “ABB Commissions World’s Longest and Most Powerful Transmission Link”, ABB press release, July 20, 2010.

[14] Nelson, J. Keith; Zenger, Walter; Keefe, Robert J.; Schadler-Feist, Sue L., US patent 7579397

[15] Asplundh, Gunnar et al; US patent 5517378 “Direct Current Breaker for High Power into a Direct Current Carrying High-Voltage Line,” May 14, 1996

[16] 2007 National Electrical Safety Code (NESC) Standard Number: C2-2007 ISBN: 978-0-7381-4893-9

[17] Barthold, L.O.; “Technical and Economic Aspects of Tripole HVDC” Powercon2006; 22-26 October, 2006 Chongqing China

[18] The entire July 2010 issue of the Journal of Energy Security is devoted to the strategic competition of China for energy resources; in particular China has a common interest in Iranian natural gas exports with India and Pakistan. Recent indications are that a cooperative deal for a single large gas pipeline serving China, India, and Pakistan is feasible.

[19] “Maghreb rail conference in Tunis”; Railways Africa, May 2010, p13; see http://www.railwaysafrica.com/

[20] This is a DOE priority: GRIDS technology was the subject of a recent US Department of Energy ARPA-E funding opportunity: http://www.governing.com/grants/energy/Gridscale_Rampable_Intermittently_27921.html

[21] Fink, S.; Mudd, C.; Porter, K.; Morgenstern, B.; “Wind Energy Curtailment Case Studies”, NREL/SR-550-46716, October 2009

[22] Faulkner, Roger W, “Evaluation of a Pumped Storage Facility Operating Between Lake Erie and Lake Ontario,” presented at the Energy Storage Association meeting, May 22, 2009

[23] Kirby, B.J.; “Frequency Regulation Basics and Trends”, ORNL/TM-2004/291, December 2004

[24] http://www.alcoa.com/massena_operations/en/home.asp

[25] Faulkner, Roger; Towler, Brian; “Hybridizing HVDC Transmission with Large Dispatchable Loads to Achieve Low-Cost GRIDS”, DOE ARPA-E Round #3 Concept Paper, April, 2010

[26] Towler, Brian; et al; DOE ARPA-E Round #1 Concept Paper

[27] Towler, Brian; et al; three related US patent applications, numbers 20100024433; 20100024381; 20100024378; “System and Method of Operating a Gas Turbine Engine with an Alternative Working Fluid”