VERY LOW IMPEDANCE (VLI) SUPERCONDUCTOR CABLES: CONCEPTS, OPERATIONAL IMPLICATIONS AND FINANCIAL BENEFITS

A White Paper
November 2003

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ABSTRACT

An aging and inadequate power grid is now widely seen as among the greatest obstacles to efforts to restructure power markets in the United States. In light of new and intensifying pressures on the nation's power infrastructure, industry and policy leaders are looking to new technology solutions to increase the capacity and flexibility of the grid without further raising system voltages. High Temperature Superconductor (HTS) cable is regarded as one of the most promising new technologies to address these issues. Among HTS cable designs, one in particular – shielded cold dielectric cable – offers performance advantages particularly well suited to today's siting, reliability and performance challenges.

Shielded cold dielectric HTS transmission cables feature very close spacing between the conductor and shield layers of wire in a coaxial cable. This close spacing results in several advantages: lower electrical losses; the virtual elimination of stray EMF; and significantly lower impedance than conventional cables and lines. Triaxial cables suited for distribution-voltage, high-current applications exhibit similar benefits. Of particular importance, the very low impedance (VLI) inherent in cables of coaxial or triaxial design makes it possible to control power flows over VLI circuits. These circuits inherently attract power flows, offloading adjacent, higher-impedance conventional circuits. Thus, for example, VLI superconductor cable ("VLI cable") offers a means of "pulling" power away from heavily-loaded lines onto high-capacity pathways that flow directly into congested urban centers. This approach offers compelling advantages compared to the traditional strategy of "pushing" power into load centers using multiple, large overhead circuits with higher impedance ratings. In addition, variable impedance may be cost-effectively added to VLI circuits with relatively small, conventional phase angle regulators. Thus, VLI circuits can function like fully controllable DC circuits, but without the expense and complexity associated with AC-DC terminal stations.

The introduction of VLI cable enables new approaches to important challenges in grid management. The strategic insertion of relatively short segments of VLI cable to bridge bottlenecks can offload flows from overburdened conventional circuits, thereby expanding grid capacity, extending the useful life of conventional network elements, and raising overall asset utilization. Important economic, environmental and policy benefits include the following:

- VLI cable users will pay less to solve power flow problems with shorter lengths of cable, at lower voltage ratings, and with greater controllability. Siting options for new generators will be expanded, and grid bottlenecks will be eased, improving overall power system efficiency and lowering total system costs.
- Adoption of VLI cable will lead to enhanced system fuel efficiency and reduced air emissions, the elimination of stray EMF, and a much smaller physical footprint for grid expansion projects, because VLI cable can be routed underground within a variety of existing rights-of-way.
- Unobtrusive VLI cable offers a new way to achieve several important objectives. It can help to break the logjam over transmission siting; improve overall power system reliability; enhance power market competitiveness; attract merchant transmission investment; and advance environmental objectives.

Initial VLI superconductor cable projects now underway provide an opportunity to develop a reliability record and resolve system integration and other implementation issues. However, to speed the commercialization cycle for VLI cable, it is urgent to expand the range of demonstration projects and identify early commercial opportunities. With power markets in turmoil and transmission increasingly the center of attention, VLI cable is a breakthrough technology with great potential to solve many of the industry's most pressing problems.

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Introduction

An aging and inadequate power grid is now widely seen as among the greatest obstacles to efforts to restructure power markets in the United States. Utilities and users face several converging pressures, including steady load growth, unplanned additions of new generation capacity, rising reliability requirements, sharp price volatility resulting from new competitive forces, and stringent barriers to siting new facilities, particularly extra-high voltage (EHV) equipment. In light of persistent challenges to proposals for conventional grid expansion, and the recognition that industry reforms cannot succeed without renewed grid investment, new technologies that can increase the electrical capacity and flexibility of this vital network are attracting increased attention. Interest in new, low-profile technologies to solve grid reliability problems intensified after the massive blackout of August 14, 2003, which highlighted the importance of power system reliability and the extent to which the margin for error in this critical system has been eroded by falling investment.

One of the technologies with the greatest promise to address these concerns is high-capacity, underground high-temperature superconductor (HTS) cable capable of serving very large power requirements at medium voltage ratings. Over the past decade, several HTS cable designs have been developed and demonstrated. All HTS cables have a much higher power density than copper-based cables. Moreover, because they are actively cooled and thermally independent of the surrounding environment, they can be fit into much more compact installations than conventional copper cables, without concern for spacing or special backfill materials to assure dissipation of heat. This advantage reduces environmental impacts and enables compact cable installations with three to five times more ampacity than conventional circuits at the same or lower voltage. In addition, HTS cables exhibit much lower resistive losses than occur with conventional copper or aluminum conductors. Despite these similarities, important distinctions do exist among the various HTS cable designs. This paper focuses on the operational, financial, and siting advantages of cold dielectric HTS cables that transmit alternating current (AC) power with very low impedance (VLI).

Principal HTS Cable Architectures

Interest in the field of superconducting power cable dates to the 1960's, but because conventional metallic superconductors required cooling with liquid helium, these cable system designs were unduly complex and cost-prohibitive. Interest in the field was renewed following the discovery of ceramics-based high-temperature superconductors in the late 1980's, which enabled the use of liquid nitrogen as a cooling medium. Liquid nitrogen is widely used in a variety of industrial applications and is recognized as a cheap, abundant and environmentally benign coolant. Nitrogen is an inert gas that constitutes 79% of the atmosphere. Additional discussion of environmental and safety issues associated with its use can be found in Technical Appendix B-1.

Over the last several decades, a variety of cable designs were prototyped and developed to take advantage of the efficiency and operational benefits of superconductivity, while minimizing the additional capital and operating costs that result from the requirement that HTS cables be refrigerated.[1] Variations in cable architecture have important implications in terms of efficiency, stray electromagnetic field (EMF) generation, and reactive power (Volt Ampere Reactive or VAR) characteristics. At present there are two principal types of HTS cable. The simpler design is based on a single conductor, consisting of HTS wires stranded around a flexible core in a channel filled with liquid nitrogen coolant. This cable design (Figure 1) employs an outer dielectric insulation layer at room temperature, and is commonly referred to as a "warm dielectric" design.[2] It offers high power density and uses the least amount of HTS wire for a given level of power transfer. Drawbacks of this design relative to other superconductor cable designs include higher electrical losses (and therefore a requirement for cooling stations at closer intervals), higher inductance, required phase separation to limit the effects of eddy current heating and control the production of stray electromagnetic fields (EMF) in the vicinity of the cable. Most of the HTS cable demonstrations undertaken to date have been based on the warm dielectric design.

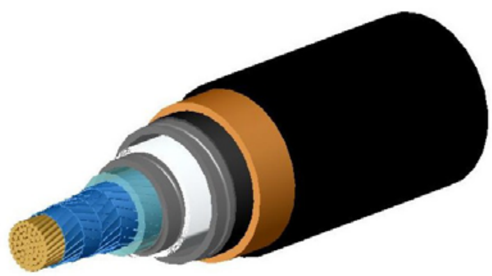

Figure 1. Single-phase warm-dielectric cable

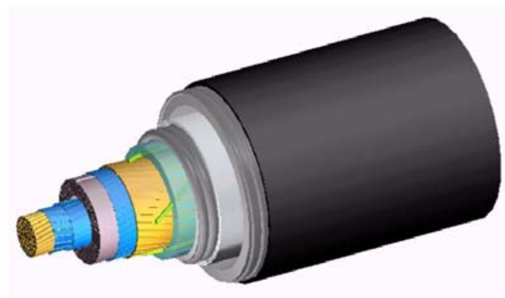

Figure 2. Single-phase cold-dielectric cable

An alternative design (Figure 2) employs concentric layer(s) of HTS wire and a cold electrical insulation system. Liquid nitrogen coolant flows over and between both layers of wire, providing both cooling and dielectric insulation between the center conductor layer and the outer shield layer. This is commonly referred to as a coaxial, "cold dielectric" design. Cold dielectric HTS cable offers several important advantages, including higher current carrying capacity; reduced AC losses; low inductance; and the complete suppression of stray electromagnetic fields (EMF) outside of the cable assembly. The reduction of AC losses enables wider spacing of cooling stations and the auxiliary power equipment required to assure their reliable operation.

[1] As discussed further herein, the net energy balance of HTS cables is very dependent upon the specific application and change in load flow associated with a given installation. Although HTS cables reduce electrical losses, these savings are counterbalanced by cooling-related costs. Therefore, relative to the other benefits discussed below, the reduction of energy losses in the transmission function, in and of itself, is not considered a principal driver for using HTS cable.

[2] The HTS layer wrapped around the inner liquid nitrogen pipe is first contained within a thermal insulating layer (cryostat). The electrical insulation is applied over the outer (room-temperature) wall of the cryostat.

Recently-published research on several cable development programs and reliability issues[3] highlights the dramatically lower impedance of coaxial, cold-dielectric HTS cable. Impedance in an electrical transmission circuit determines the power flow division among many cables connected in parallel. Power flow in a circuit is inversely proportional to its impedance. Thus, other factors (applied voltage and phase angle) being equal, a low-impedance HTS cable will carry more load than a conventional cable connected in parallel to the same two points on the grid. Two or more lines of equal impedance will carry equivalent amounts of power; when the thermal capacity of one of the lines is reached, no more power may safely be permitted to flow, lest that line become overloaded and fail. The inductive impedance of cold-dielectric cable is up to six times lower than that of conventional cable, and twenty times lower than an overhead line of the same voltage (see Table 1).

Further technical discussion related to cable inductance, and the behavior of cold dielectric HTS cables under fault conditions, is contained in Appendix A. The remainder of the body of this paper focuses on the operational benefits of VLI cable designs that warrant special consideration, particularly in light of the challenges facing today's power transmission sector.

A Comparison of Power Transmission Technologies				
Technology	Resistance (Ω/km)	Inductance (mH/km)	Capacitance (nF/km)	(MVAR/km)
Cold Dielectric HTS	0.0001	**0.06**	200	1.08
Conventional XLPE	0.03	0.36	257	1.4
Overhead Line	0.08	1.26	8.8	0.05

Table 1. Electrical characteristics of HTS Cold Dielectric cable, XLPE cable and conventional overhead line (source: Jipping, J. et al, "Impact of HTS Cables on Power Flow Distribution," cited in Footnote 1). (120kV class cable) Capacitance values in MVAR/km have been added to this table. (Note: see Footnote 3 regarding differences between these values and the values contained in a comparable table in Appendix A-1.)

This low impedance property is specific to cables that employ both HTS wire and a coaxial cable geometry. In other words, VLI cables may be arranged in a 3-in-1 "triplex" design or, a 3-in-1 “Triaxial” design or, alternatively, may occupy separate ducts (Figure 3); the VLI characteristic results from the thin electrical insulation with closely spaced return conductors and is independent of the arrangement of phases with respect to each other.

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[3] See, for example, Jipping, J. Mansoldo and Wakefield, "The Impact of HTS cables on Power Flow Distribution and Short Circuit Currents Within a Meshed Network." IEEE (2001). A table contained within that paper (reproduced herein as Table 1) drew attention to the low impedance advantage of coaxial cable. New calculations of cable impedance contained in the present paper (see Appendix A-1) are based on an actual cable under development for installation on the Long Island Power Authority (LIPA) grid in 2005, and reflect a more conservative cable design. The impedance calculations for cold dielectric cable made by Jipping et al. are feasible based on further, foreseeable improvements in insulation systems. See also, Silberglitt, R., Ettedgui and Hove, "Strengthening the Grid: Effect of High-Temperature Superconducting Power Technologies on Reliability, Power Transfer Capacity and Energy Use," RAND Corporation Science and Technology Policy Institute (2002).

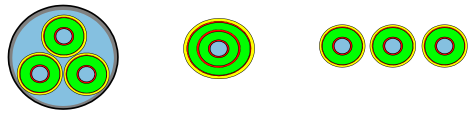

Figure 3. Both the "Triplex" cable on the left, consisting of three coaxial conductors comprising an AC circuit, as well as the triaxial cable in the center and the circuit on the right (three coaxial cables in separate ducts) will exhibit low inductance. Inductance is a function of the spacing between the phase conductor and shield layer, rather than the phase-to-phase spacing.

As discussed above, the low impedance benefit associated with coaxial or triaxial designs depends upon the thin electrical insulation where shielding currents constrain the magnetic fields to a small volume. For optimum cable performance, this shield layer should completely and imperviously surround the conductor layer, eliminating the escape of any flux whatsoever. However, as a practical matter, there is likely to be some minor leakage in the shield layer resulting from spacing between the wires. The low levels of leakage flux will not impair cable performance, or the advantages of the VLI design, to any meaningful extent. See further discussion of this issue in Appendix A-2.

The low impedance benefit is also maximized from an absolute standpoint when all three phases of an AC system are perfectly balanced. From a practical standpoint, of course, AC transmission systems are constantly, if slightly, out of balance as a result of such factors as moment-to-moment variations in customer use patterns. At transmission voltages, these slight imbalances may cause negligible increases in line impedance ratings above a theoretical minimum (consequences on distribution systems close to customer loads are likely to be somewhat larger). In practice, the imbalances that occur on high-voltage transmission networks (69 kV and above) rarely if ever exceed 5%, and in the high power end of distribution networks, the imbalance is below 10%. At such inconsequential levels, phase imbalances are not likely to have more than a negligible impact on overall cable performance.

The type of connection employed between a low-impedance cable and the conventional system may, in theory, affect its absolute level of impedance in the course of operation. However, cables *per se* do not control how other types of equipment (such as transformers and generators) are connected at their ends; cables simply connect two parts of a power system. The end equipment could be delta or star connected on both ends and cable performance will not be affected (unless the cable's shield is connected to the end equipment ground). Small net shield currents will flow within the cable shield circuit if the 3-phase currents are not balanced, but these are not expected to change the low impedance of each phase, provided the shields are properly grounded (see Appendix A).

Effects of VLI Superconductor Cables on Power Grid Flows

The power density and siting advantages generic to all HTS cables have been well understood for several years. The implications of low impedance in cold dielectric HTS cables, however, are less broadly known. Compared to conventional overhead lines, underground copper cables, or unshielded HTS cables, the most distinctive capability of VLI cable is its **controllability**. When inserted into networks consisting of conventional elements with higher impedances, VLI cables will act as "current hogs," naturally attracting current or power flows.[4] In fact, if not modified, insertion of these cables into networks that already have existing parallel paths with higher impedance ratings will sharply reduce the amount of flow that would otherwise be borne by these other conventional network elements.[5]

From a transmission planning perspective, this "current hogging" attribute is a double-edged sword. To the extent planners have considered low impedance in the past, they have tended to view it as a potential liability because it results in large system normal and contingency power flows. In fact, the full capacity of a VLI cable upgrade may not initially be usable because the cable can immediately represent the single largest contingency on the system.

Viewed from a different perspective, however, low impedance can offer important advantages. Under some circumstances, it can be much easier and less expensive to "pull" power onto high-capacity pathways that flow directly into a congested load pocket, through a low-impedance cable, than to site, construct and "push" comparable quantities of power to the same spot on the grid using conventional approaches.[6] In addition, impedance may be added to a VLI circuit, simply and inexpensively, by installing conventional substation equipment, e.g., inductors or PARs, yielding effective and economical control of flows over "current hogging" VLI cables. Thus, VLI superconductor cables can be **configured to function like fully controllable DC circuits**, while operating in the synchronous AC environment -- thereby avoiding the cost of AC/DC converter stations. In addition, small and less expensive phase angle regulators (PARs) can achieve the same degree of control over a VLI circuit as the larger, costlier phase shifting equipment needed for a conventional circuit. Moreover, it would be feasible to develop compact, integrated HTS PARs that could fit into the congested areas of a power grid. In short, VLI cable introduces the prospect of an unobtrusive, low-impact and fully controllable transmission solution, operating at HV transmission voltages or distribution voltages within the existing AC environment.

The introduction of VLI cable into the transmission planner's arsenal also suggests a potent new strategy for expanding grid capacity. As thermal transfer limits are reached on power grids, congestion bottlenecks appear. Historically, utilities have preferred to relieve these bottlenecks, when possible, by constructing overhead lines which are typically the least-cost solution. However, this approach is becoming increasingly difficult, particularly in urban areas, because of siting restrictions. Moreover, recent experience has shown that bottlenecks often arise in and around urban areas where the combination of short distances and high real estate costs make HTS cable a viable alternative solution. In such situations, power flow problems could be solved by overlaying the existing, conventional network of lines and cables with relatively short,

[4] During faults, VLI cable inductance is similar in magnitude to conventional cables and, thus, fault currents are no greater than in conventional cables (and may be lower to the extent that fewer circuits would be required for a given load).

[5] In some situations, such parallel path circuits may not already exist, due, for example, to difficulty of access, limited space or environmental issues. In these situations, the principal benefit of an HTS cable insertion may be its high power rating, rather than its low impedance.

[6] As used here, the concepts of “pulling” and “pushing” power are relative terms. Under the laws of physics, power flows from generation to load via all available parallel paths, in inverse proportion to the impedance of each circuit. Power flows will tend to be “pulled” onto the circuits with the lowest impedance ratings, until they are fully loaded; strictly speaking, power is not “pulled” toward the load.

strategic insertions of VLI cable across these congested interfaces.[7] This approach would draw currents away from other conventional grid elements operating at or near their limits. By reducing high current flows and associated overheating on existing lines, VLI cables can slow or prevent the dielectric breakdown, annealing and other processes that often cause conventional cable or lines to age and fail. Employing such a strategy judiciously will increase grid capacity, extend the useful life of conventional network elements, and improve overall asset utilization -- all at lower cost and with much less environmental impact than would result from a conventional strategy of wide-area network upgrades.

As with any type of grid enhancement, the usefulness of VLI cable will depend upon a situation-specific analysis. In some applications, the VLI attribute will provide a major benefit in facilitating flows and relieving congestion. At the same time, in other applications, the very low impedance of the cable may lead to undesirable changes in power flow, and/or require additional investments in compensation equipment that may mitigate or neutralize the VLI benefit. Thus, VLI cable should not be regarded as a universal solution, but rather as a targeted solution that is most effectively applied after careful evaluation of conditions in the surrounding grid.

It is also important to note that the capacity of a single VLI cable circuit inserted into a grid may not be fully usable because of contingency considerations. In fact, the addition of a new high-capacity VLI cable may initially create the largest single contingency on a system. In this respect, the incorporation of a single, high-capacity VLI cable into an existing network is conceptually similar to adding the first line of a new and higher voltage level into a conventional system (e.g., adding a 765 kV line into a 345 kV system). However, as additional VLI cables are added, the usable capacity of other VLI elements in the same network may be increased. Each successive VLI cable insertion, in other words, will tend to increase the usable capacity and contribution to reliability of previously-installed VLI cable elements.

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[7] Like conventional underground cables, HTS cables are likely to be used on relatively short runs in AC applications due to the effects of charging currents. Charging current, a function of the capacitance per unit length, becomes the predominant component of total current flow when cable lengths approach 20-25 miles, resulting in a natural limit on the length of underground circuits. This physical limitation can be overcome by bringing cables above ground and adding reactors (or SuperVAR™ synchronous condensers) to supply inductive compensation. While technically feasible, the additional cost of such an approach is likely to make it applicable only in those areas where extremely high real estate prices or other siting obstacles make overhead transmission impossible.

VLI Superconductor Cable Case Study: Urbanized Load Pocket

The benefits of this concept for using VLI cable can be illustrated by considering a case study.[8] A utility provides service to an area that includes a congested, urbanized "load pocket." It has encountered thermal limits on total power deliveries into the area due to a combination of load growth and local generator retirements. To increase service to the affected area, the utility plans a 50-mile, EHV overhead transmission line looped from the existing regional backbone EHV network. The expected cost of this solution, driven predominately by high local real estate values, is approximately $250 million, or $5 million per mile[9]. Given local community opposition and the presence of physical siting obstacles, routing is necessarily circuitous and there is a high degree of project completion risk.

The utility investigates VLI cable as an alternative solution to deliver a comparable level of power into the heart of the congested area. It develops an alternative solution that flows power directly, in a highly targeted fashion, into the heart of the congested area over the VLI circuit. Because of the higher ampacity of the cable, the utility finds that it can deliver comparable MVA levels at lower HV (115/138/161 kV) voltages. This enables re-use of an existing right-of-way without the special permitting requirements often associated with EHV projects. In addition, because the utility's HV (115/138/161 kV) network is more pervasive than the EHV network, it can find a point of interconnection that is much closer to the heart of the load pocket.

The alternative VLI solution requires a ten-mile segment of unobtrusive, underground VLI cable plus associated power flow control equipment. If a conservative cost of $10 million per mile on an installed basis (including ancillary equipment) is assumed for VLI cable, the overall solution is $100 million or 60% lower than the conventional solution.[10] In other words, even though VLI cable can be more expensive than conventional solutions on a mile-for-mile basis, the ability of VLI superconductor cables to solve power flow problems with shorter lengths of cable, at lower voltages and in a shorter timeframe due to simplified siting and permitting requirements can provide offsetting advantages that lead to lower installed-cost system solutions. While VLI cable remains an early-stage, low-volume product, initial projects are likely to be focused on highly congested grids in urban areas. As volumes increase and costs decline, its advantages can be expected to expand to a broader range of applications.

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[8] This illustration, while fictionalized, is based on an actual situation with comparable values.

[9] Overhead transmission construction costs have become highly variable across the nation, differing by a factor of five or more based on such factors as real estate values, availability of right of way, terrain, electrical configuration, mitigation requirements and the level of community opposition. A standard 345-kV circuit in a rural area, where there is no siting opposition, may cost as little as $1.2M-$1.5M per mile. Physically identical facilities in an urbanized area, however, are commonly quoted at $3-4M per mile and have been projected to cost as much as $7.5M per mile (ISO New England RTEP02, November 2002, p. 16, item 4.26). Underground conventional transmission facilities, meanwhile, which may cost $5M per mile in a non-urbanized area, have been estimated to cost as much as $15M per mile in congested areas (e.g., metropolitan New York). “Soft” costs (real estate, mitigation, permitting and litigation) often represent 70-80% of the cost of a conventional cable installation. The total installed cost for an HTS cable system, by contrast, is likely to be dominated by the cost of the cable itself. Because of the compact size of HTS cable installations and the ability in some instances to reuse existing underground infrastructure, “soft” costs are expected to be significantly lower.

[10] As VLI cable technology matures, per-mile installed costs are expected to fall well below this level.

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Addressing the Single Contingency Problem: Power Flow Control on VLI Cable

As mentioned above, the use of VLI enables power flow to be diverted from conventional cables or overhead lines to the HTS cables during both system normal and contingency situations. To control the flow of power on the HTS circuit, it is possible to employ a variety of conventional devices -- e.g., series inductors, variable inductance series reactors or phase angle regulators (PAR) (as shown in black in figure 4). An inductor limits power flow by increasing HTS cable circuit impedance and a phase angle regulator controls power flow by controlling the phase angle voltage applied to the HTS cable circuit.

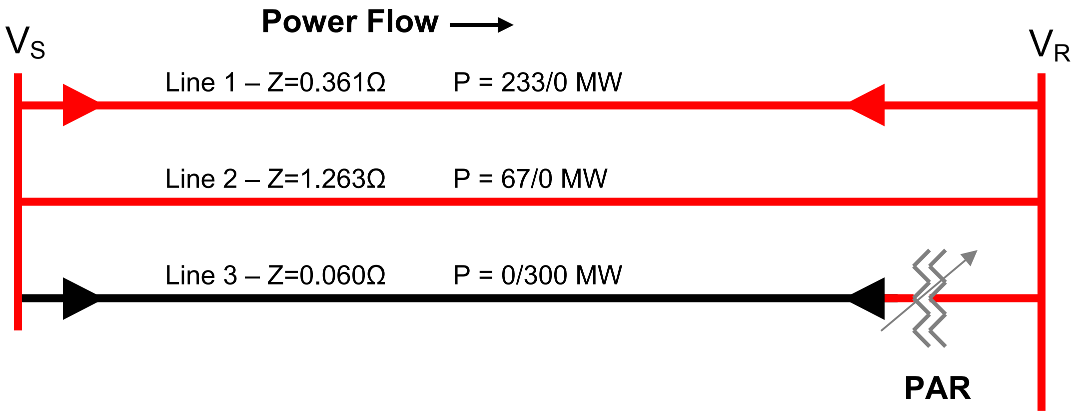

Figure 4. A phase angle regulator (PAR) on a 138 kV VLI cable that is inserted in parallel to two conventional lines connecting V_S and V_R (line 3) enables the division of power flow between three circuits to be continuously modified, enabling a precise level of power flow control over a wide range of settings. For example, with only the first two lines present, a sending power of 300 MW, and with the indicated series impedances (assumed to be inductive), lines 1 and 2 carry 233 and 67 MW respectively. When the third VLI HTS line is added, the three lines carry 41, 12 and 247 MW respectively. A PAR in line 3 can increase the power flow in line 3 to 300 MW and reduces the power flow in both lines 1 and 2 to essentially zero. Switching in a series inductor instead of the PAR also allows a significant degree of power flow control, although not as flexibly as with a PAR (e.g., control of flows from 247 MW to much lower levels in line 3, depending on the inductance; or to 0 by simply opening the line).

The use of phase-shifting equipment to modulate power flows on an AC network is not new in and of itself. Phase-shifting equipment has been employed on power grids since the 1930's.[11] Because of uniquely low impedance of VLI cable, however, the use of PARs on VLI circuits will

[11] While phase angle regulators have been employed for several decades, they have often not been a favored solution, in part because of the size and expense of the required equipment. Perhaps more importantly, outside of the Northeast and Middle Atlantic regions where planning has been conducted on a pool basis for several decades, the U.S.utility industry has been marked by its fragmented structure. This lack of close coordination may have impeded the adoption of PARs because their use by one company can threaten offsetting and uncompensated effects on the transmission system of neighboring utilities. This problem is being addressed by the Federal Energy Regulatory Commission's ongoing initiative to form Regional Transmission Organizations (RTOs) with a more unified approach to grid operation. This initiative is expected to result in grid operations with more regard for optimizing flows from a regional perspective. In this new environment, the value of technologies that enhance power flow control, and result in lower net costs on a regional basis, is expected to be more readily apparent.

enable a given degree of power flow control to be achieved with a much smaller angular adjustment (by a factor of 6-7 times). For example, a 40 MW change in power flow may require a six-degree phase angle shift on a typical 115 kV circuit. By comparison, a similar 40 MW change in power flow could be achieved through a one-degree shift on a VLI circuit of comparable capacity. This means that large, costly phase angle regulating equipment used to effect desirable levels of power flow control can be replaced with smaller, less expensive phase angle regulating equipment. Conversely, much larger changes in power flow (if desirable and feasible in light of system-wide impacts) can be achieved on a VLI circuit than on a conventional circuit, for any given degree of angular shift.

The type of regulating equipment best suited for a particular application may vary depending upon the degree of controllability required, as well as budgetary considerations. Simple, low-cost series reactors, for example, could be used at low cost to add impedance and reduce flows on a VLI cable circuit with regard to other paths. This approach may be sufficient in situations, for example cables exclusively serving loads in dense urban areas, where two-way flows are never contemplated. By contrast, somewhat more costly phase angle regulators could be used to change the relative phase angle either positively (to increase flow) or negatively (to inhibit flow. In some situations, for example merchant power applications, this two-way controllability may be particularly important. Because relatively small PARs could be used to achieve a significant degree of control over a VLI circuit, PARs are likely to offer both a highly flexible and cost-effective strategy for controlling VLI circuits in many applications.

While VLI circuits will have high theoretical capacities compared to conventional circuits, the extent to which this capacity is usable will be governed by standard transmission planning considerations. These include the maximum fault current level of the system (typically, maximum fault current ratings range from 65kA to 80kA) as well as the ability of the underlying system to handle the post-contingency flows resulting from an outage of the VLI circuit itself. Interestingly, VLI cable has the feature that in fault situations, its impedance reverts to the conventional value, so that it does not contribute to enhanced fault current. Furthermore, as has been noted previously, post-contingency flow will be a potential limiting factor particularly in the case of the installation of the first VLI circuit in a given electrical pathway. If additional VLI circuits are added, each independent circuit will provide a redundancy benefit to the underlying system. This problem of handling post-contingency flows is a factor in the design of any transmission element, and concerns about post-contingency flows related to VLI cable are a matter of degree, not of kind. VLI circuits will need to be designed to assure proper power pickup following contingencies, in accordance with the criteria (e.g., N-1 or N-2) employed for a particular system. In this respect, the design of VLI circuits is no different than the design of conventional circuits.

<u>VLI Superconductor Cable: Economic and Financial Benefits</u>

Using VLI cables in new solutions for power flow problems can translate into significant cost savings. As described above, the factors that lead to lower costs on an installed system basis may be summarized as follows:

- Shorter lengths. Short, strategic insertions of VLI cable could achieve the **same power flow benefit** as lengthier circuits of overhead line. VLI cable need not be cost-competitive with conventional cable or overhead line technology on a stand-alone basis for it to offer a lower total cost solution. For example, with VLI cable utilities may solve power flow problems with shorter circuit lengths, e.g., connecting to the more pervasive 115/138/161 kV system rather than tying back to the more distant EHV backbone transmission system.

- Lower voltages. Because of the higher capacity of VLI cable (approximately three to five times higher ampacity than conventional circuits), utilities may employ lower-voltage equipment, avoiding both the electrical (I^2R) losses typical of high-current operation and the capital costs of step-up and step-down transformers (as well as the no-load losses within the transformers themselves). High-current VLI cables at 115 kV or even 69 kV may solve problems that would ordinarily require a 230 kV or 345 kV conventional solution. The ability to operate at lower voltages translates into **lower costs** for cable dielectric/insulating equipment, reduced hazards, as well as lower cable and ancillary costs, which are driven by the voltage level of the selected solution. In the long run, VLI may obviate the much higher system costs (e.g., transformer and breaker replacement) associated with wide-area voltage up-ratings.

- Greater controllability. VLI cable offers the ability to control power flows with conventional series reactors or PARs, yielding market and reliability benefits typically associated with other "controllable" forms of transmission -- e.g., FACTS (Flexible AC Transmission Systems) or DC transmission. Yet this control at the termini of a line would be achieved with much less expense and complexity than is typically required using conventional technologies (e.g., large, inflexible DC converter stations or the large-scale power electronic devices often associated with conventional FACTS devices). Whereas DC lines are limited to point-to-point flows, VLI cable systems could be expanded to provide controllability to many points in a network.[12] This inherent controllability has **important regulatory implications**. For example, VLI could form the basis for private, at-risk investment in merchant transmission projects with assignable property rights in transmission capacity, outside of the rate base framework, in situations where DC and conventional FACTS solutions are not cost-competitive. The cost of DC systems is highly impacted by the cost of converter stations. For short runs of DC transmission, system costs are dominated by the cost of converter stations; VLI cables face no such penalty.

- Life extension and improved asset utilization. VLI cable represents a new weapon to attack the principal enemy of congested urban transmission systems: heat. Over time, thermal overload ages and degrades cable insulation. By drawing flow away from overtaxed cables and lines, strategic insertions of VLI cable can "**take the heat off**" urban power delivery networks that are increasingly prone to overheating, the inevitable result of increased loadings and acute siting difficulties associated with siting conventional (copper or

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[12] In some cases it may be desirable or necessary to employ DC transmission, for example, to facilitate flows between asynchronous regions. Use of VLI cable within the confines of a synchronous region is not incompatible with this use of DC transmission; in fact, these two strategies could be employed on a complementary basis to enhance the reliability and stability of power grids on a wide-area basis.

aluminum-based) system expansions. [13] Reducing the burden on existing electrical pathways will extend the life of conventional system elements. This approach also improves overall asset utilization, and defers the need for the large-scale capital investment required for the replacement of aging and worn-out grid infrastructure.

- Expanded generator siting options. Because it greatly reduces voltage drop, low-impedance VLI cable has the ability to "shrink electrical distance". This means that new generators could be located at greater distance from urban loads (where land, labor and other costs are lower), while providing the same degree of voltage support as if they were located in or adjacent to the city center. Thus, HTS transmission lines could be deployed as "**virtual generators**" to solve both power supply and reactive power problems.

- Reduced electrical losses. In specially optimized designs, VLI cable can result in lower net energy losses than occur in either conventional lines and cables or unshielded HTS cables with a single conductor per phase, offering a transmission path with **high electrical efficiency**. Because VLI circuits tend to attract power flow, they will naturally operate at a high capacity factor, reducing the losses on other circuits and further magnifying their efficiency advantage.

- Indirect and non-monetary savings. In addition to these "hard cost" savings, VLI cable may result in other "soft cost" savings. For example, time to install may be shortened because of **reduced siting obstacles** associated with compact underground installations and less burdensome siting requirements for lower-voltage facilities.[14] VLI cables might be routed through existing, retired underground gas, oil or water pipes, through existing (active or inactive) electrical conduit, along highway or railway rights-of-way, or through other existing corridors. While HTS cables “off-the-shelf” are likely to cost more than conventional cables, the net cost of a fully installed cable system may be lower because of the smaller space requirements associated with HTS cables, and the ability to make adaptive reuse of existing infrastructure where it exists, or the ability to use guided boring machines instead of costlier and more disruptive trenching where such infrastructure does not exist. The expansion of siting options would reduce the need for costly and controversial expropriation proceedings. Indirect impacts on property values resulting from overhead line construction would also be avoided. Communities that host VLI projects would gain the benefit of higher property valuations, e.g., higher property tax receipts and broader development options.

- Reduced regional congestion costs. Finally, and perhaps most significantly, the ability to complete grid upgrade projects more quickly will translate into the **earlier elimination or relaxation of grid bottlenecks**. Solving physical bottleneck problems will sharply reduce the grid congestion costs that, in today's unsettled, imperfectly competitive marketplace, can impose huge penalties on consumers and the economy at large.

[13] VLI cable is not the unique solution to the problem of overheating; this condition can be avoided or mitigated by many forms of system expansion, including either conventional or VLI elements. In reality, however, conventional upgrades requiring significant amounts of space, and/or siting approval, have become extremely difficult to implement for political, social and other reasons.

[14] Although permitting and regulatory requirements vary from state to state, it is generally the case that lower-voltage and reconductoring projects enabled by HTS cable are easier to site and permit than new EHV installations. Because HTS cable is an unfamiliar technology that operates at cryogenic temperatures using liquid nitrogen as a coolant, it will be necessary to address and resolve public and regulatory concerns prior to widespread adoption. An overview of safety and environmental issues associated with liquid nitrogen can be found in Technical Appendix B-1.

VLI Superconductor Cable: Environmental Benefits

Beyond the cost advantages outlined above, VLI cable will yield several environmental advantages over conventional technology. Some of these advantages are due to the very same characteristics of VLI cable that result in lower-cost installed solutions. For example:

- Underground placement. The underground placement of VLI cable will **eliminate the visual impact** of overhead lines.

- Shorter cable lengths. Solving power flow problems with shorter lengths of cable in more compact rights-of-way will **reduce the disruptive effects of construction**.

- Reduced losses. The reduced losses in VLI circuits, as well as reduced I^2R losses on adjacent, conventional circuits that are offloaded due to the "current hogging" effects of VLI cable, will translate into **reduced fuel consumption** for generation.

- Environmentally benign dielectric. Liquid nitrogen, the coolant/dielectric of choice for VLI cables, is inexpensive, abundant and environmentally compatible.

Other environmental benefits associated with VLI are less direct and harder to quantify, yet can still be decisive in determining a utility's ability to complete a project. For example:

- Elimination of EMF. The coaxial design of VLI cable, coupled with the HTS shield, **completely suppresses electromagnetic fields** (EMF). The shielding of phase currents that typifies the VLI design results in counteracting and mutually canceling fields. As a result, and as verified by laboratory measurements, VLI cables generate minimal to zero EMF (i.e., below ambient levels) outside of the compact cable assembly. Stray EMF elimination has the benefits of avoiding eddy current losses from nearby metallic conduits or other metallic structures, eliminating interference with any surrounding electrical cables, whether for power or telecommunication, and making the cable circuit inductance completely independent of the configuration of the phases.

- Enhanced generator dispatch. Perhaps the most significant environmental benefit associated with the use of VLI is the relaxation of constraints on generator dispatch arising from expanded grid capacity. As has become evident over the past few years, grid constraints can force costly reliance upon older, dirtier so-called "reliability must-run" (RMR) generating units located in the heart of populated, urbanized areas. These RMR generators typically have higher heat rates and emissions than state-of-the-art generators. Relaxation of these dispatch constraints will translate into **lower regional air emissions and fuel costs**, which will positively impact both public health and utility rates. While transmission reinforcements of all types offer this benefit, VLI cable upgrades may be feasible in situations where other types of grid upgrades cannot be permitted. Neither VLI cable nor any other form of grid reinforcement can eliminate the need for local generation capacity for certain systemic reasons (e.g., local voltage support, blackstart capability); however, strategies that enable reduced operating levels for these RMR facilities can yield significant economic and environmental benefits.

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Policy Implications of VLI Superconductor Cable

Policymaking officials in the power arena recognize the need for new solutions to manage power flow problems. For several years, electricity policy reform efforts focused on alternatives to transmission expansion -- e.g., demand-side response, distributed generation, or the placement of bulk generators in congested locations -- due to concern that grid expansion represents the most difficult of all challenges. Episodic price spikes, the emergence of generator overcapacity, and the recent financial turmoil of the merchant power sector signal the shortcomings of this approach. The failure to expand the grid to keep pace with the steady growth in power demand has been costly to power producers, consumers, investors and the nation's economy as a whole. Low-profile VLI cable enables a new approach to many of the most pressing energy policy challenges, including siting new infrastructure, assuring overall system reliability, promoting robust competition, and assuring a strong measure of environmental protection.

- Transmission siting. With rising real estate costs, landowner and community opposition to power infrastructure projects, power transmission right-of-way represents one of the scarcest resources in the entire energy system. As the nation strives to redefine and modernize its energy policies, proposals to federalize the process of expropriation to secure new rights-of-way for large overhead transmission facilities have proven to be one of the greatest points of contention between state and federal officials. While policy debates focus on the merits of shifting siting jurisdiction to a new battlefield, VLI cable represents a new technology tool that can reduce if not eliminate the need for controversial takings and siting processes. Such attributes as compact size, the possibility of shorter cable lengths, underground placement, elimination of EMF, and ready integration into the existing AC system will **ease siting requirements**. These attributes will also make it possible to use existing power corridors and other rights-of-way for system expansion, or secure new rights-of-way with less public opposition.

- Improved reliability. By making grid expansion feasible in constrained locations, VLI cable addresses the paramount need for increased capacity and improved power system reliability. A steadily growing fraction of U.S. energy consumption takes the form of electric power. As recently as 1970, a quarter of the nation's end-use energy needs were met with electricity; by 2000, that proportion had reached 40% and is projected to reach 50% within the next fifteen to twenty years. Moreover, the nation requires not simply more power, but more reliable, higher-quality power to meet the needs of today's digital economy. The strategy of inserting VLI cable into existing conventional grids to expand the grid's capacity and extend the life of existing system elements represents one of the **most effective and least disruptive** ways to meet this imperative.

- Enhanced competition. After a quarter-century of bipartisan reform efforts to bring greater competition into the energy arena, power market restructuring efforts are stalled. By offering a new approach to expand grid capacity and fortify competitive market discipline, VLI cable offers policymakers a new tool to regain lost momentum. At present, efforts to bolster competition in power markets are complicated by the need for regulatory intervention to police the behavior of market participants. Federal and state regulators are struggling to define appropriate policies to prevent the undue exercise of market power, particularly in load pockets where grid infrastructure is weakest and most difficult to expand. Expansion of grid infrastructure with VLI cable and other solutions represents **a structural remedy** that can reduce the need for regulatory intervention. By expanding the effective reach and market options of producers and consumers alike, VLI cable can limit the opportunity to exercise undue market power, reducing the need for controversial regulatory review of and intervention in market operations.

- Environmental protection. Steady growth in power consumption, and rising concern about air emissions (particularly greenhouse gas emissions), makes it critically important to find new strategies to improve power system efficiency. By expanding grid capacity and relaxing grid dispatch constraints, VLI cable will improve access to the most thermally-efficient forms of generation, wherever they may be located. Relaxation of "reliability-must-run" constraints will also enable reduced reliance on older, dirtier generating units that must run for grid support but that typically have the highest rates of harmful emissions. The use of VLI cables, with low voltage drop over very long distances, will make it possible to supply power to dense urban centers from generators in more distant locations where costs are lower. This strategy of "**shrinking electrical distance**" will improve air quality and public health in the areas where populations are most concentrated.

The efficiency and environmental benefits that arise from easing grid dispatch constraints are indirect and difficult to quantify; these benefits are separate from, and in addition to, the efficiency and environmental benefits that arise from the improved transmission efficiency, or permittivity, of low-loss VLI cables.

In summary, VLI cable offers a new strategy to increase power system capacity and thereby expand the “solution space” for grid planners and operators. How this increased capacity is used will depend upon the objectives determined by planners, operators and regulators in a given area. For example, the same increase in capacity may be used entirely for the purpose of improving reliability margins, or to increase transfer capacity, or for some optimal combination of both purposes. Faced with a number of pressures that have limited system operating flexibility in recent years, utility planners may look upon VLI cable as a new, low-environmental-impact strategy to regain some of the necessary flexibility that has been lost to these trends.

Conclusion

As power transmission problems have intensified across the nation's grid over the past few years, the need for new technology solutions has become apparent. For several years, leading government authorities and industry organizations, such as the U.S. Department of Energy and EPRI, have focused on the potential to use HTS cable to address grid congestion issues and achieve a higher degree of power market integration. Most analyses to date have focused on the high ampacity, small physical profile and ease of siting common to all types of HTS cable.

This paper, while acknowledging those benefits, has focused on an additional attribute that is unique to VLI superconductor cable: its high degree of controllability. Given today's acute level of concern about system reliability and new competitive pressures, policymakers and market participants recognize that strategies to control and redirect transmission flows have greater value than ever before. As detailed above, the use of VLI cable in conjunction with low-cost, conventional power flow control equipment provides a means to achieve this goal. Until now, such control could only be obtained with much more costly DC or FACTS technology. By taking advantage of VLI cable's controllability, utilities and regional transmission operators will find new and less expensive ways to tackle grid congestion problems, reduce grid security violations, improve overall asset utilization and extend the life of their existing systems.

The widespread commercial adoption of VLI cable has great potential to generate a range of economic, environmental and reliability benefits, many of which are discussed herein. Yet, as is often the case with many "breakthrough" technologies that are initially high-cost, early developers and users face high risks. These risks are compounded by the very uncertainties and regulatory complications that VLI cable could ultimately help to resolve. It is important, therefore, to undertake all appropriate steps to speed the commercialization of this promising technology. A series of demonstration projects to illustrate the power flow attributes of VLI cables, to develop a reliability record for the technology, and to resolve system integration and other issues, should be a top priority of public officials responsible for transmission-related policy.

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Appendix A.

The following section contains technical information regarding the calculation of cable electrical characteristics.

A-1. Cable Inductance and Capacitance

The inductance and capacitance of a coaxial cable can be calculated from the basic equations of electromagnetism.[15] The inductance is proportional to the integrated magnetic field energy stored around the conductor. In the case of a coaxial VLI HTS cable, the magnetic field is contained entirely in the narrow cylindrical space between an inner HTS conductor, (at a radius from R_1 to R_2), and the HTS shield conductor (at radius R_s). This assumes that the shield conductor is grounded, and it is designed so as to carry a reverse current which can fully compensate the current in the inner conductor, with negligible flux leakage through shield.

An approximate result for the inductance (L) per length (in units of H/m) is[12]

$$L = \frac{\mu_o}{4\cdot\pi}\cdot\tan(\theta)^2 + \frac{\mu_o}{2\cdot\pi}\cdot\ln\left(\frac{R_s}{R_2}\right) + \frac{\mu_o}{2\cdot\pi\cdot\left(R_2^{\,2} - R_1^{\,2}\right)^2}\cdot\left[\frac{R_2^{\,4} - R_1^{\,4}}{4} + R_1^{\,4}\cdot\ln\left(\frac{R_2}{R_1}\right) - R_1^{\,2}\cdot\left(R_2^{\,2} - R_1^{\,2}\right)\right] \quad (1)$$

where
R_1 = inside radius of the inner conductor
R_2 = outside radius of the inner conductor
R_s = shield radius
θ = pitch angle of inner conductor helical winding
μ_o = permeability of free space (1.257×10^{-6} Henries/meter).

The first term represents a contribution to the inductance from the helical winding of the cable conductor and is usually negligible.[16] The third term represents the contribution from the finite thickness of the inner conductor; it is also negligible in the VLI HTS case because the HTS windings are very thin. Therefore the dominant term is the second term. An example of typical dimensions[17] and the resulting inductance for a VLI HTS cable is given in Table A-1, with the cable sized for 2000 A_{rms}. Because each phase is fully shielded, the result is essentially independent of the spatial configuration of the different phases, whether they are in isolated ducts or grouped together in a triplex configuration. If the spacing between the inner conductor and the shield is further reduced, an even smaller inductance can be calculated, as in the work of Jipping et al.[3]

Eq. 1 can also be used to calculate the inductance of a conventional copper cable, although now the result depends strongly on the cable configuration. Let us consider the case of a three phase cable system with grounded shields around each phase. While cables for some special applications carry a full return current, more typically the current-carrying capability of the shields is designed to be much less than in the HTS case; they must only carry a portion of transient fault current, and, on a continuous basis, only 10% of the rated current (reflecting the

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[15] J. C. Das, Power System Analysis (Marcel Dekker Inc., New York 2002), p. 737
[16] S. K. Olsen et al., Loss and inductance investigations in a 4-layer superconducting prototype cable conductor, IEEE Trans. on Applied Superconductivity, Vol. 9, No. 2, June 1999, pp. 883-836
[17] These data are derived from the HTS cable currently being designed for installation in the Long Island Power Authority grid in 2005; lower inductances for VLI cable are envisioned at a later stage of product development. See, in this regard, Table 1 and footnote 3 in the main text.

need to handle so-called “zero sequence currents.”) This means that the shields are typically relatively thin, providing minimal containment of magnetic flux. As a result, the total inductance is much higher and has contributions from the mutual inductances of the different phases; it depends on the spatial configuration, specifically on whether the three phases are grouped in a triplex (triangular, in cross section) configuration in a single conduit, or on whether each phase is in its own separated conduit, and on whether the conduit is conducting, magnetic (iron) or insulating.

If each phase lies in a separate duct well separated from the others, it is common to define an effective radius field capture, usually assumed to be about 12 inches or 30 cm.[12] To apply Eq. 1 to this case, R_s is taken to be this field capture radius. The inductance for this case, calculated from Eq. 1 and ignoring any field capture from the shield or contribution from the duct, is shown in Table A-1 as “conventional XLPE”; it is approximately six times higher than the VLI HTS case.

A different result applies to three XLPE phases grouped within a single conduit. An estimate for the inductance in this configuration can be obtained from Eq. 1 by taking the relevant effective radius R_s to be approximately the separation between each of the phases; the calculated inductance will then be two to three times lower than before. However, in this case the rating of the XLPE cable is reduced significantly because of heating in the three closely spaced phases; so the need for a high capacity interconnection cannot be met. Another scenario could be to run, say, three 200 MW 138 kV XLPE cables in parallel to match the 600 MW capacity of one VLI HTS cable; in this case the combined XLPE inductance is also reduced by a factor of three from the value for a single XLPE cable; however this solution requires significantly increased right of way as compared to the VLI HTS solution and has additional costs compared to a single cable solution. Therefore, in practice, these alternatives for achieving low inductance with conventional cables rarely apply.

The case of an HTS warm dielectric cable is similar to the conventional copper cable because its room temperature copper shield is also thin and does not contain the magnetic flux; so the inductance can be calculated in a similar manner, and gives very close to the same result as conventional XLPE for separated phase configuration in Table A-1. Finally, for an overhead line with no shield at all, the inductance estimated in Table A-1 is yet higher because of the increased separation between the phases.[18]

The cable capacitance C per length (in units of F/m) is calculated using the following equation.

$$C := \varepsilon_o \cdot \frac{2 \cdot \pi \cdot \varepsilon_r}{\ln\left(\frac{R_s}{R_c}\right)} \qquad (4)$$

where R_s – radius of shield (m)
R_c – outside radius of conductor (m)
ε_o – permittivity of free space
ε_r – dielectric constant

In summary, the data in Table A-1 show that the self-inductance of the particular HTS coaxial cold dielectric cable design whose dimensions are given in the table is about 6 times less than a

[18] The Electric Power Engineering Handbook, L.L. Grigsby, CRC Press and IEEE Press, 1998 (see discussion on page 10-40)

corresponding conventional cable or warm dielectric HTS cable and about 10 times less than that of an overhead line. The capacitances of HTS and conventional cables are comparable.

Cable Type	Cable Dimensions			Electrical Characteristics		
	Inside Radius	Outside Radius	Shield Radius	Resistance	Inductance	Capacitance
	(mm)	(mm)	(mm)	(Ω/km)	(mH/km)	(nF/km)
Conventional XLPE	2	25	40	0.03	0.83	140
HTS Warm Dielectric	12.7	14	29	<0.0001	0.86	250
HTS Cold Dielectric (VLI)	12.7	14	29	<0.0001	**0.15**	150
Overhead Line	2	10	20000	0.08	1.46	8

Table A-1: Electrical characteristics of various power transmission technologies operated at 138kV. The self inductance and capacitance are calculated for a single-phase conventional XLPE cable, a single-phase HTS warm dielectric cable, an HTS coaxial cold dielectric (VLI) cable and a conventional overhead line. Note that all of the cables are shielded; however only the cold dielectric cable has an HTS shield, grounded and thick enough to contain all the magnetic flux. Other cables have room temperature copper shields, which are assumed not to contain magnetic flux appreciably. Dimensions for the HTS cables[14] are sized for 2000 A; dimensions for conventional technologies are illustrative.

A-2. Effect of Non-Continuous Shielding Layer on VLI Superconductor Cables

The HTS shielding layer is constructed by helically wrapping HTS wires over the cold dielectric of the co-axial cable. A finite amount of spacing is left between adjacent tape-shaped wires in order to permit bending of the finished cable during transportation and installation operations. This spacing is typically less than 5% of the width of the tape-shaped HTS wire. A typical HTS tape is about 4 mm (160 mil) wide and therefore the spacing between adjacent HTS tapes is about 0.2 mm (8 mils). Any leakage of field outside the HTS shield will be on the order of 5%, and this will be further attenuated by roughly 50 mils of additional copper shield which will usually be added and which has a skin depth of 30 mils at 77K. So the net impact on the previously calculated inductance will be negligible.

A-3. HTS Cable Inductance During a Fault

An important issue is whether the low impedance of VLI superconductor cables will increase fault currents in the grid. VLI cables can be constructed by wrapping HTS wires around a stranded conventional copper conductor as shown in Figure A-1, and copper shield wire is also wrapped around the HTS shield. During a fault, the cable current is expected to reach up to 60,000 A. It is a fundamental property of HTS conductors that under fault conditions, they immediately transition to a normal state once the current exceeds the critical current. As the current increases, this normal state is initially a moderately low resistivity state called the flux flow state, but once the current exceeds several p.u., the full normal state resistivity of order 100 μΩcm is reached. Under fault conditions, these transformations can occur within milliseconds, that is well within a single AC cycle. Then all current is shifted to the copper core (and copper shield wires, if necessary). Thus, during the fault, the superconducting cable has effectively become a normal cable with cryogenic copper.

Now, the inductance of the cable when the current only flows in the copper core is similar to the inductance of a conventional cable. In other words, during the fault, the HTS cold dielectric cable inductance increases by a factor of order 5, similar to that of a conventional cable. Therefore, we have the very important conclusion that a VLI cable will not add to the fault loading, and fault currents will be very close to those expected for conventional cables.

Furthermore, under fault conditions, the surge impedance of a VLI cable is about 30 ohm which is similar to that of conventional cable. If the cable rated current (=2500A) is suddenly removed then the cable line voltage will rise to 130kV (=30 ohm*2500A*1.73)[19] which is less than the rated cable voltage (138kV). The copper core can be designed with adequately low resistance to minimize the heat rise during typical fault conditions and allow the system to recover on return to operating current levels. Even after a single phase fault, the three-phase VLI cable can be designed such that the inductive impedance of the faulted phase recovers essentially immediately, even though the resistive impedance may take several minutes to return to its original condition. Similar considerations will apply to any other transients which may induce currents of several times the operating current level. In summary, VLI HTS cables will need to be fully tested under fault conditions, but are expected to function in a manner consistent with conventional copper-based cables.

A-4. Other HTS Cable Design Issues

In a cold dielectric cable, the insulation is at liquid nitrogen temperature (77 K). BIL and impulse strength of insulations in liquid nitrogen were studied as part of the DOE Resistive Cable Program in GE during the 1970's; there was no significant difference found between liquid nitrogen and oil impregnated insulations systems.

Another important issue in cable design is the effect of current imbalances in three phase systems. Since many kinds of terminations (delta, wye) are possible at the two terminations of the cable, there are many different types of current imbalances that can occur. However, if the shields of each phase of a VLI cable are grounded at both ends, then each phase remains uncoupled (no mutual inductance) from the others, and the inductance of each phase is preserved. Other grounding schemes may be possible depending on the type of termination.

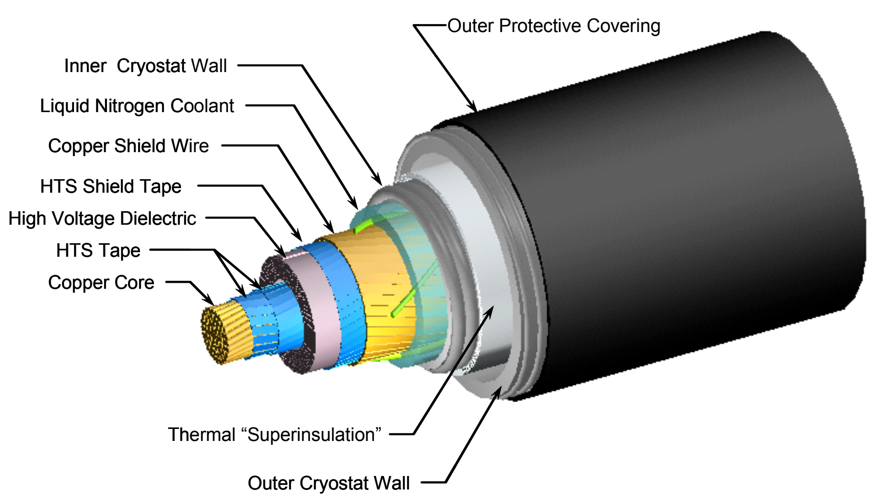

Figure A-1: Cross-section of a HTS coaxial cold dielectric (VLI Superconductor) cable with solid copper core to carry fault currents

Appendix B.

This section contains information regarding health and safety considerations associated with liquid nitrogen, as well as planning considerations that arise from the use of HTS cables.

B-1. Health and Safety Considerations Related to Liquid Nitrogen

Nitrogen is a colorless, odorless, stable and non-flammable gas that occurs naturally in the atmosphere. It constitutes approximately 79% of the earth's atmosphere and, under normal conditions, poses no threat to health or safety. When cooled, nitrogen condenses into a liquid at a boiling point of -195.8 C (-320.4 F, or 77 K); it is abundant in nature and routinely made available as a byproduct of oxygen liquefaction (the boiling point of oxygen is 90 K). Because it is abundant, low-cost, non-corrosive, non-flammable and has high electrical insulating properties, liquid nitrogen is an ideal coolant and dielectric for electric power applications of superconductors.

There are two principal risks associated with nitrogen: oxygen deficiency and extreme low temperature. Release of high concentrations of nitrogen into the environment, in confined spaces, can result in asphyxiation by displacement of oxygen. Raised concentrations of nitrogen may cause a variety of respiratory symptoms and, at high concentrations, unconsciousness or death may occur. Direct contact with liquid nitrogen can cause frostbite-type injuries, and must be avoided. The low temperature of liquid nitrogen can also result in a temporary fog that will lower temperatures and obscure vision until it dissipates. If a spill or leak occurs in a non-confined space, nitrogen will rapidly dissipate into the environment. There are no known adverse health effects associated with chronic exposure to this gas.

In order for HTS cable to be adopted on a widespread basis, several design options are available for minimizing the risk of accidental exposure to liquid nitrogen or excessive concentrations of gaseous nitrogen. These include the following:

a) The area above an HTS cable should be protected with some means of deflecting backhoe hits, in much the same way that conventional underground cables and high-pressure gas pipelines are protected and marked. Concrete, wood or steel barriers, with an audible and/or visual warning system in case of physical contact, would reduce the incidence of accidental dig-ins.

b) A system of sensors along the length of a LN-filled cable system could be employed to detect low temperatures, low concentrations of oxygen, or both.

c) Careful monitoring of coolant flow, temperature, and pressure can be used to determine the presence of a leak or fault.

Such systems could be used to detect slow leaks, drops in vacuum pressure, or catastrophic failures along the entire length of an HTS cable, using low-power remote telemetry capable of being powered by solar panels. In the event of a system failure, a signal can be sent to issue an alarm and/or shut off the flow of liquid nitrogen into the cable if this is deemed appropriate.

Further information describing the physical properties, hazards and special handling considerations associated with liquid nitrogen can be readily found on the material safety data sheets (MSDS) maintained by several large air liquefaction companies (e.g., Air Liquide, Praxair, Air Products) and available on their websites.

B-2. Planning Considerations Associated With Use of HTS Cable

As described in the body of this paper, HTS cables are actively cooled with liquid nitrogen. Active cooling prevents some of the heating-related issues that commonly give rise to grid reliability problems, yet creates a requirement that cables be maintained in a refrigerated state. Thus, the introduction of HTS cable into a power grid offers advantages as well as disadvantages in terms of assessing overall system reliability. Following is a summary of some of the considerations that planners and operators will need to consider as they contemplate incorporating HTS links into existing grids.

Operation beyond rated capacity. Because of the virtual absence of I^2R losses, HTS cables are unlike conventional cables in that they are not subject to failure in the course of normal operation due to "runaway" overheating associated with high currents. On the contrary, the capacity of HTS cables can be effectively increased beyond their nominal rating, albeit at an increased cost of operation, by increasing the flow of liquid nitrogen, lowering its feed temperature, or both, to compensate for the watt-level increases in losses associated with high-current operation. HTS cables can be operated in this mode indefinitely without any permanent degradation of capacity, although the increase in operating costs makes it likely that this operating mode would only be used during peak or emergency periods.

Response to loss of cooling. There are various modes of possible failure in the cooling system (for example, refrigerator, circulation pump, compressor or cryostat failure). Commercial cryocooling systems are routinely designed to deal with these various contingencies. Industrial gas industry practice is to provide a reserve of cryogenic coolant to continue to provide cooling in the event that the primary cooling system for an HTS cable fails (and assuming the line is not broken). Furthermore, if both primary and reserve cooling systems were to fail, under most conditions the line could be operated normally for a period of several minutes, allowing time for orderly reconfiguration of the grid and de-energization of the circuit. In a de-energized state, because of its thermal mass, the cable will then gradually warm over a period of hours or days. Although the cable can continue to operate for some period after a loss of coolant, it is important to take the cable out of service promptly before this occurs, to avoid damage to the cable.

As would be the case with any type of conductor, in the event that a line is severed (for example, due to a dig-in), service will be immediately interrupted. Underground placement, clear marking and encasement in a protective conduit can reduce but not eliminate the risk of severed lines.

Service restoration. A disadvantage of HTS cables is that they cannot be immediately restored to service after a repair to a circuit because of the need to reach cryogenic temperatures to achieve the superconducting state. Cryogenic coolant reserves and access to the nation's extensive industrial gas infrastructure for the supply of cryogenic liquids can reduce the cool-down period. However, a cool-down period of at least several hours is likely to be required following the repair of an HTS cable, and service to customers in the vicinity of an HTS cable that has been subjected to such an outage will need to be provided through alternate pathways until the design operating temperature is achieved.

Cooling technology. The necessity to maintain cooling to cryogenic (liquid nitrogen) temperatures introduces a new type of failure mode for the HTS cable itself. This fact requires a highly reliable design for HTS cable cooling systems, both at the component level and at the system level. At the component level, conventional coolers to achieve liquid nitrogen temperatures have been employed by thousands of users for several decades, with a high degree of reliability. Many of these coolers are in unattended operation at remote locations, in conditions similar to those that would typify utility grid operations. Cryocooler technology is employed across a number of industries, and widespread utility adoption of HTS cable (e.g., several thousand miles of cable) would result in an incremental increase in the user base. To facilitate broader use of cryocooler technology, work is underway to develop lower-cost, highly-reliable, modular pulse tube refrigeration systems with the fewest possible moving parts. At the system level, cooling networks will likely need to be designed that incorporate redundancy, reflecting the same N-1 type of approach that is reflected in overall transmission system design. Existing business models, for example involving the outsourcing of reliable cooling systems, supported by existing infrastructure and managed by industrial gas suppliers, can be used to ensure that HTS cable systems are operated reliably and at least cost. All in all, cooling technology is sufficiently well developed and widely deployed in industry that this is not seen as a major obstacle to achieving a highly reliable VLI transmission cable; however, appropriate systems must be designed and tested at the fully commercial level.

Conclusion. As this discussion indicates, the adoption of HTS cable technology promises to improve overall power system reliability in many ways, yet because it introduces new failure modes, adoption of the technology will introduce new types of risks that must be managed. It is likely that adoption of HTS cable technology will offer the greatest improvement to system reliability if it is deployed in strategic insertions to supplement and fortify the existing network, rather than to replace large parts of it. Furthermore, as a result of the power of network effects, the reliability benefits of HTS cable are likely to compound as the technology is propagated through a grid. While the capacity of initial insertions of HTS cable into a grid may not be fully usable because of contingency concerns, subsequent additions will tend to increase the effective contribution to reliability of already-installed HTS links. For a fuller discussion of the relative advantages of using HTS cable to supplement rather than to replace existing grids, see, for example, "Strengthening the Grid: Effect of HTS Power Technologies on Reliability, Power Transfer Capacity and Energy Use" (RAND Corporation, op. cit.), pp. 26-34.

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Author Organizations

About American Superconductor Corporation (NASDAQ:AMSC)

AMSC is a world-leading supplier of dynamic reactive power grid stabilization products and the world's principal vendor of high temperature superconductor (HTS) wire and large rotating superconductor machinery. AMSC's power electronic converters and HTS wire are at the core of a broad range of new electricity transmission and distribution, transportation, medical and industrial processing applications, including dynamic reactive power grid stabilization solutions, large ship propulsion motors and generators, smart, controllable, superconductor power cables and advanced defense systems. The company's products are supported by hundreds of patents and licenses covering technologies fundamental to Revolutionizing the Way the World Uses Electricity™. More information is available at www.amsuper.com.

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Nexans is the worldwide leader in the cable industry. The Group brings an extensive range of advanced copper and optical fiber cable solutions to the infrastructure, industry and building markets. Nexans cables and cabling systems can be found in every area of people's lives, from telecommunications and energy networks, to aeronautics, aerospace, automobile, railways, building, petrochemical, medical applications, etc. With an industrial presence in 28 countries and commercial activities in 65 countries, Nexans employs 17,150 people and had sales in 2002 of euros 4.3 billion. Nexans is listed on the Euronext Paris stock exchange. More information on www.nexans.com

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Oak Ridge National Laboratory is a multiprogram science and technology laboratory managed for the U.S. Department of Energy by UT-Battelle, LLC. It supports the Department of Energy's mission, including neutron sciences, high-performance computing, complex biological systems, electricity transmission and distribution, and materials science. More information about ORNL may be found at www.ornl.gov.

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Sumitomo Electric Industries, Ltd. was founded in April, 1897, and has been a world leading electric wires and cables manufacturer for more than a century. Consolidated net sales were 1,488,914 million Yen as of March 2003. SEI is also a leading manufacturer of optical fiber products, network equipments, electro-optic components, sintered products, including synthetic diamonds, and semiconductors. More information is available at www.sei.co.jp/welcome_e.html.

About Ultera

Ultera is a joint venture between two of the world's leading wire and cable companies, Southwire Company of Carrollton, Ga. and *nkt cables* of Denmark. Ultera was created to continue the successful development of high temperature superconducting power cable technology independently initiated by both Southwire and *nkt cables*. The combined resources of Ultera represent the only two successful HTS cable installations in the world to provide power to residential, commercial and industrial users. Ultera has more than five years of day-to-day operational experience with HTS cable systems providing power to end users in the United States and Denmark. More information is available at www.mysouthwire.com and www.nktcables.com.