Superconductivity White Paper

A cost-effective way to upgrade urban power networks while protecting the environment

NOTE: This document is a condensation and substantial update of an original collective White Paper, entitled *Very Low Impedance (VLI) superconductor cables: concepts, operational implications and financial benefits* (2003)

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Synopsis

This White Paper presents some recent developments in superconductivity and explains how Nexans is serving this market.

It opens with the blackout question, and explains how high temperature superconductors (HTS) can contribute to the resolution of this problem. Secondly, it describes HTS cable architectures and explains the effects of superconductor cables on power grid flows. Thirdly, it presents some current case studies and relates other Nexans superconductor developments, concluding with economic, financial and environment benefits. Finally, it explains policy implications of superconductor cables.

I. INTRODUCTION: PRESSURES AND PROMISES

Pressures on power grids

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, Europe and elsewhere. Utilities 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 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.

Blackouts, and superconductivity's potential to resolve them

In 2003, a series of dramatic energy blackouts occurred in both North America and Europe, largely due to a sudden demand for air-conditioning or heat. In the old days, these surges would have been handled by a regional utility having the *plant margin* necessary to immediately rectify a sudden rise in demand. However, since electricity has become a commodity, purchasable anywhere according to best price and the time of the day, power utilities have started to squeeze their plant margin in order to make savings both in power generation expenses, and infrastructure reinvestment.

In many cases, when demand for more power suddenly rose, the situation was further complicated by component failures, slow corrective action, low water levels, untimely power plant interruptions (for maintenance), storms, mis-rated fuses, and undersized transmission lines. Inadequacies like these caused overheating in transmission lines which quickly sagged onto poorly trimmed trees. Then further non-action and computer failures quickly cascaded these energy failures upwards, so that massive areas were affected, like the American Midwest, Northeast and a large part of eastern Canada. In Italy, similar cascading events, together with overloads, created a large blackout in Europe.

Over the past three years, there has been an ongoing series of major blackouts worldwide, especially in 2006: the most dramatic being in Queens, New York (July), Karachi, Pakistan (September) and northwestern Germany, Paris, and 15 French regions (November). The European blackout was the most dramatic power failure in three decades, plunging millions of European into darkness, halting trains, trapping dozens in elevators, and prompting calls for better integration of energy across the continent.

The real reasons behind these events are often inadequate transmission and distribution networks (due to underinvestment) and the inability of various grids to smoothly manage power handoffs. This was the real wake-up signal that the blackouts provided. Power Utilities or Transmission Operators have to start upgrading their grids, especially for critical high-voltage, long-distance transmission. In the dense city environment, new short-link technologies like superconductivity can contribute to significantly increasing power potential.

The promise of high temperature superconductors (HTS)

One of the technologies with the greatest promise to address these concerns is the high-capacity, underground High-Temperature Superconductor (HTS) cable which is capable of serving very large power requirements at medium and high-voltage ratings. Over the past decade, several HTS cable designs have been developed and demonstrated. All of these 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 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 HTS cables that transmit Alternating Current (AC) power with Very Low Impedance (VLI).

II. PRESENTATION OF SUPERCONDUCTOR CABLES

HTS cable architectures

Interest in the field of superconducting power cable dates back 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 ceramic-based high-temperature superconductors in the late 1980's, which enabled the use of liquid nitrogen as a cooling medium at about -200°C. 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.

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 (see Figure 1) employs an outer dielectric insulation layer at room temperature, and is commonly referred to as a "warm dielectric" design.[1] 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.

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[1] 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.

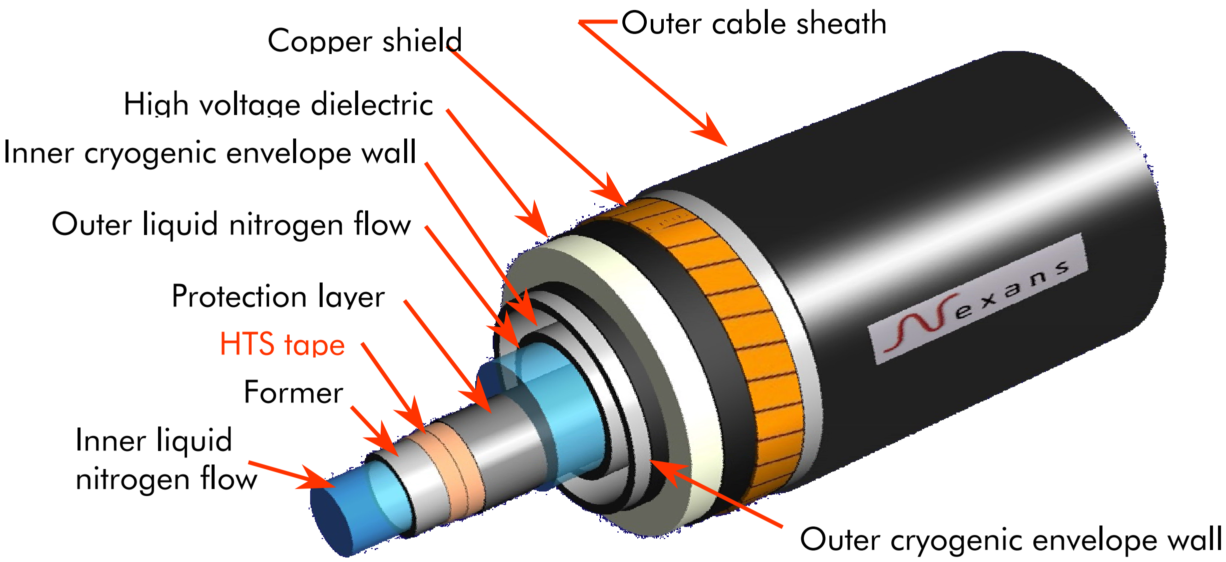
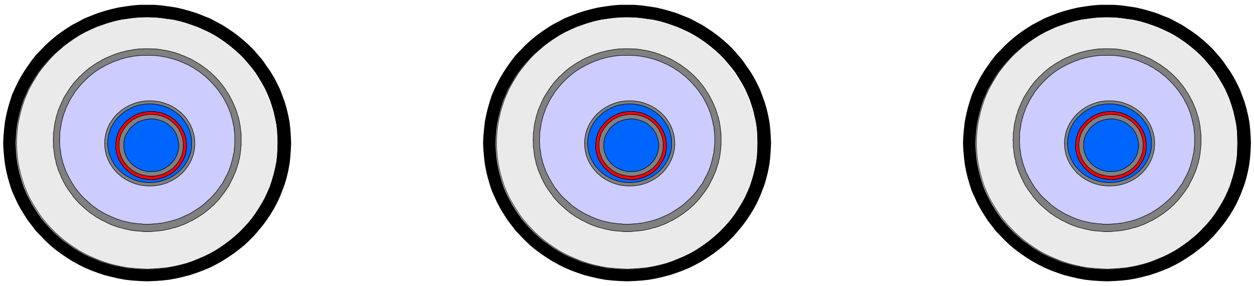


Figure 1. Single-phase warm-dielectric cable

Electric and Magnetic Fields require that there be spacing between the phases. This kind of warm dielectric HTS design is more desirable for medium voltage installation.

3 separate phases



An alternative design (Figure 2) employs concentric layer(s) of HTS wire and a dielectric material, providing electrical insulation, compatible with cryogenic temperatures. Liquid nitrogen coolant flows over and between both layers of wire, providing cooling and contributing to the dielectric insulation between the center conductor layer and the outer shield layer. As the dielectric material remains at about -200°C, this cable architecture is commonly referred to as a coaxial, "cold dielectric" design. Such cables offer 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.

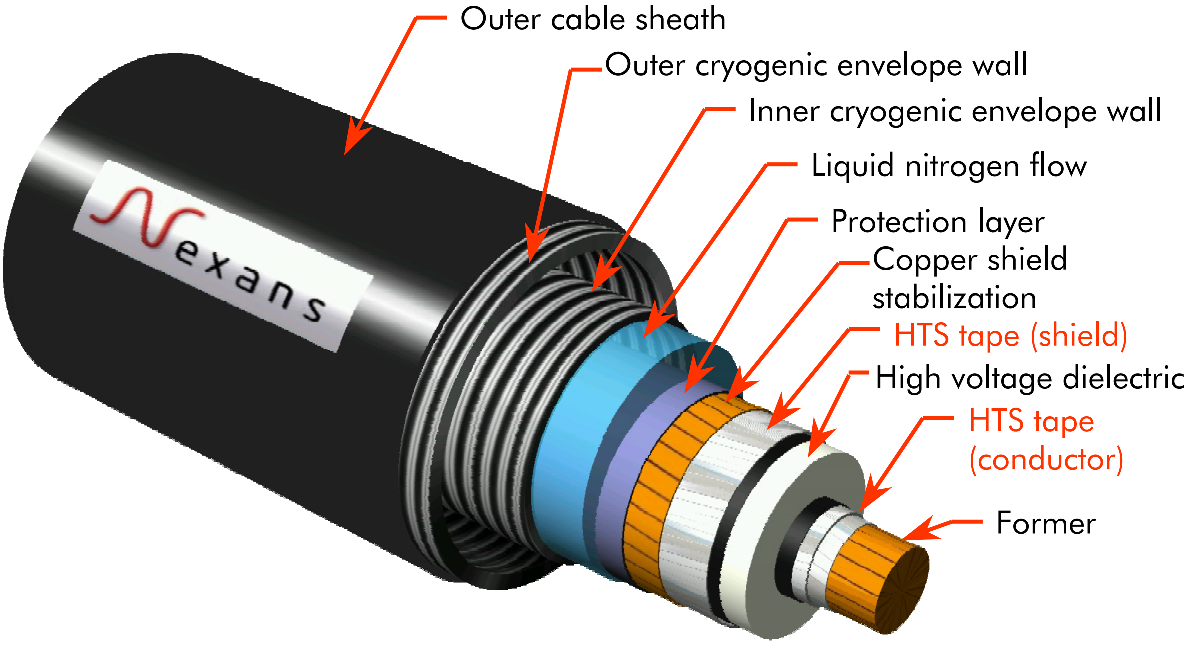


Figure 2. Single-phase cold-dielectric cable

Recently-published research on several cable development programs and reliability issues highlights the dramatically lower impedance of coaxial, cold-dielectric cables. 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 coaxial HTS cable will carry more load than a conventional cable connected in parallel to the same two points on the grid. The inductance 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).

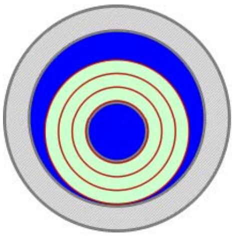
A Comparison of Power Transmission Technologies

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

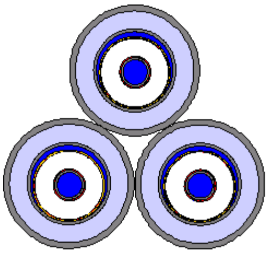
Table 1. Electrical characteristics of HTS Cold Dielectric cable, XLPE cable and conventional overhead line (source: Jipping, J. et al, "Impact of HTS Cables on Power Flow Distribution,"). 120kV class cable.

This low impedance property is specific to coaxial HTS cables. However, such Very Low Impedance (VLI) cables may be arranged in three alternate geometries, which give additional benefits. **Concentric phases** offer no EMF and are available in a compact design which optimizes the use of HTS tapes. They are suitable for medium voltages. **Three phases in one cryogenic envelope** offers no EMF in a compact design. Shrinkage and expansion take place within the cryogenic envelope. This geometry is suitable for medium voltages and the lower part of high voltages. Finally, **three separate phases** have no EMF and can achieve the longest unit lengths. This alternative is especially suitable for high voltages.

Concentric phases



3 separate phases



Three phases in one cryogenic envelope

Effects of VLI superconductor cables on power grid flows

Compared to conventional overhead lines, underground copper cables, or unshielded HTS cables, the most distinctive capability of VLI cable is their **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. 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.

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 of its 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. In addition, impedance may be added to a VLI circuit, simply and inexpensively, by installing conventional substation equipment, e.g., inductors or phase angle regulators (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 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, strategic insertions of VLI cable across these congested interfaces. 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 aging, 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.

III. CASE STUDY, CURRENT TESTS AND APPLICATIONS

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 in the United States.[2] 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, Extra High Voltage (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. 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. 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.

The Long Island demonstration

In August, 2006, during a scorching heat wave, the Long Island Power Authority (LIPA) inaugurated the construction phase of the world’s largest and highest-voltage superconductor electric transmission cable system. The 138,000 volts (138 kV) cable system, 600 meters in length, will be the world’s first superconductor cable installed in a live grid at transmission voltages, and will carry more power than all previous HTS cable demonstrations combined.

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

The purpose of this project is to demonstrate the operation of a HTS cable within an actually operating electric utility transmission system. The cable will be installed in 2007 in LIPA's Holbrook transmission right-of-way, running north/south. Both ends will be connected to LIPA's existing transmission system.

The main project objectives are twofold. The first one is to identify the key issues and concerns that need to be addressed to enable HTS cables to be operated effectively in a power grid at transmission voltages. The second is to develop, design, produce and operate this HTS cable system.

When Nexans was contacted for the Long Island project, the Group decided to make full use of its technological assets and industrial tools. The results are that 1) the cable core is manufactured at the Nexans plant in Halden (Norway); 2) the cryogenic envelope is made at the Nexans plant in Hanover (Germany); and 3) the terminations in Calais (France).

Nexans is the worldwide leader in flexible cryogenic envelopes. This expertise was originally dedicated to the transfer of liquefied gas (Cryoflex® product). It was especially adapted to the world of superconducting cables.

As host utility, LIPA is providing the site engineering and preparation, as well as guidance for the design and testing of the cable system. American Superconductor is providing project management, technical input and the HTS wire for the cable. Nexans is the cable and cable termination supplier, developing, qualifying and installing cable and terminations. Air Liquide is providing the refrigeration system and installation support.

After an initial operational period, subsequent performance and economic assessment of the cable system, LIPA plans to retain the new superconductor cable as a permanent part of its grid. LIPA will eventually install HTS cables elsewhere on their grid to address the growing power needs of Long Island.

HTS cables can carry 3–5 times more power than a conventional copper cable of similar size. Thermally-independent, compact HTS cables can be installed into existing rights-of-way, thus helping to reduce the cost and environmental impact of future grid upgrades. With much lower impedance and resistance than conventional technology, superconductor cables can be strategically placed in the electric grid to draw flow away from overtaxed conventional cables, or overhead lines, thereby relieving network congestions while providing an environmentally-friendly solution.

IV. OTHER NEXANS SUPERCONDUCTIVITY DEVELOPMENTS FOR POWER NETWORKS

Second-generation superconductor cable

For the European Commission, Nexans has been coordinating a European "Super3C" (Super Coated Conductor Cable) project to develop a HTS cable using coated conductors as current carrying elements.

Coated conductors constitute the second generation of HTS wires. They consist of a metallic tape coated with ceramic layers, one being superconducting. This multilayer structure makes them significantly cheaper than the currently used multifilament tapes which require a silver matrix. The Super3C project aims at developing, manufacturing and testing a one-phase, 30-meter long, 10 kV, 1kA functional cable model.

The project team brings together partners from Finland, France, Germany, Norway, Slovakia and Spain. Nexans manufactures cable and terminations and contributes to the coated conductor tape.

Fault current limiters

Nexans is leading a consortium to develop a superconducting fault current limiter based on high temperature superconductors (HTS) for use on 110 kV networks. These fault current limiters offer new possibilities for optimizing network infrastructure by considerably improving resistance to short circuit currents.

The HTS current limiter uses superconducting material developed and manufactured by Nexans SuperConductors. At temperatures below -180° C (it's critical temperature), this material becomes superconducting and behaves like a virtually zero-impedance conductor. If, however, the ceramic metal-oxide warms up above the critical temperature, or if the current density becomes too high, it loses its superconductivity. The same happens when the superconductor is exposed to a high magnetic field. The current limiter uses these effects to automatically reduce unacceptably high currents to a pre-set value.

HTS current limiters will provide an improved network structure and cost-savings on network components. The most important application will be to couple 110 kV network groups. Currently the 110 kV network is divided into isolated network groups in order to avoid excessively high short-circuit currents. These network groups are fed through transformers from the 220 kV or 380 kV network. The number of these transformers is selected such that, if one breaks down, sufficient redundancy remains. By adding superconducting fault current limiters, network groups could be coupled and some transformers would thus become unnecessary, offering important cost savings. According to many experts, the fault current limiter may constitute the application that will propel superconductors into the mainstream.

V. BENEFITS OF VLI SUPERCONDUCTOR CABLES

Economic and financial benefits

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. 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. 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 aluminum-based) system expansions. 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.[3] 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.

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 installation. The underground installation of VLI cable will **eliminate the visual impact** of overhead lines.

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[3] Although permitting and regulatory requirements vary, 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.

- 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.

VI. POLICY IMPLICATIONS AND CONCLUSION

Policy implications of VLI superconductor cables

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 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. Such attributes as compact size, the possibility of shorter cable lengths, underground installation, 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. 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.

- 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

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. HTS cables and fault current limiters constitute new tools to develop these strategies. By taking advantage of their outstanding features, 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 these superconducting devices for power networks 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.