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Long Distance Transmission System Using VSC HVDC Terminals and Superconductors for Bulk Transport of Renewable Energy

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SUMMARY

The combination of voltage source converter (VSC) based multi-terminals operating at moderate DC voltages (≈ +/- 200kV) and underground DC superconductor cables can create a compelling new option for transmitting renewable energy over long distances with multiple collection and distribution points – a virtual, long-distance, high power bus-bar. It will be shown that such a system has the potential of transmitting 5,000 – 10,000MW or more, over distances exceeding 1500 km while exhibiting the lowest power losses of any transmission technology. When combined with conventional underground pipeline construction techniques, the system has the potential to be cost competitive with overhead EHV AC and traditional HVDC transmission technologies.

The two key power system technology components in the system are superconductor cables and VSC HVDC terminals. Superconductor cables utilize superconductor materials with current densities well over 100 times those of copper or aluminum wires of the same size. This power density difference drives system economics and is fundamental to the reason why superconductor DC cable compares favourably with conventional alternatives for long distance power transmission. When transmitting DC power, superconductors have zero electrical resistance introducing no electrical losses of their own. Superconductors must be refrigerated to exhibit their electrical characteristics. However, even including refrigeration losses, DC superconductor power cable systems can be shown to have much higher overall efficiency than any other long-distance transmission system. Moreover, unlike conventional transmission lines, their efficiency is independent of the transmission power level.

DC terminals employing VSC technology are currently available at relatively moderate (100-300kV) voltages. To be used in high power transmission with conventional copper conductors, these voltage levels require the use of very high currents. Transmission of high currents over long distances with conventional conductors will result in considerable resistive losses. DC superconductor power cables avoid this limitation by providing the ability to carry very high levels of current with zero electrical loss over essentially unlimited distances.

The superconductor / VSC-based HVDC / pipeline system makes for a compelling new transmission option, uniquely suited to transmitting renewable energy over long distances with multiple collection and distribution points. This paper presents the features of this option when compared alongside other transmission technologies including EHV overhead AC lines, underground AC cables, overhead HVDC and UHVDC, underground HVDC, and VSC-based HVDC using conventional conductors.

KEYWORDS

superconductor, HVDC, HTS, renewable energy, transmission, cable, voltage source converter.

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1. INTRODUCTION

The principal technology used today for long distance, high power transmission is high voltage overhead lines, whether alternating current (AC) or direct current (DC).

The desire to transmit large amounts of electrical energy produced from renewable resources is complicated by the large distance frequently found between renewable sources and locations of power demand. Further complicating this is the need to collect the renewable energy over a wide geographic region and to deliver it to large numbers of separate population centers. Existing transmission technologies, whether overhead or underground, are not necessarily ideal for this situation when viewed in light of challenges ranging from public opposition to siting overhead transmission lines, to political issues such as cost allocation of new lines across multiple utilities, to the power losses associated with long distance transmission.

Another transmission option - consisting of DC superconductor underground cables combined with voltage source converter (VSC) HVDC terminals - appears to address many of these issues and could be particularly well suited for the transmission of large blocks of power over long distances.

2. THE DC SUPERCONDUCTOR CABLE CONCEPT COMPONENT TECHNOLOGIES

2.1 Superconductor Cables

Superconductor cables utilize superconductor materials instead of the copper or aluminum traditionally used to carry electricity in overhead power lines and underground cables. Superconductor materials provide two operational advantages. Superconductor materials can carry well over 100 times the current density of copper or aluminum, which in turn drives system economics and is fundamental to the reason why superconductor DC cables compare favourably with conventional alternatives for long distance power transmission. Secondly, when transmitting DC power, superconductors become perfect conductors with zero electrical resistance and introduce no electrical losses of their own.

The cables would employ superconductor wires that are commercially well established and available from multiple producers globally. Superconductor cable systems are now operating in multiple in-grid sites around the world, demonstrating their reliability and performance, as illustrated in Figure 1. While all previous installations are AC applications, applying the technology to DC is straightforward.

Figure 1: 138 kV AC superconductor power transmission cable operating since April 2008 in Long Island Power Authority’s grid (photo courtesy Nexans)

With present superconductor wire manufacturing techniques, superconductor DC cable designs are possible with very high continuous power capacities of 5 to 20GW. The economics of the design favor higher power ratings; for example, a 10GW design is estimated to be less than one-third more expensive as a 5GW design. This supports the use of the superconductor DC cable as a solution more appropriate for very high power transfer situations.

Figure 2 shows a cross section of one possible design of DC superconductor cable as developed by EPRI [1]. Figure 3 shows typical underground pipeline construction and burial methods.

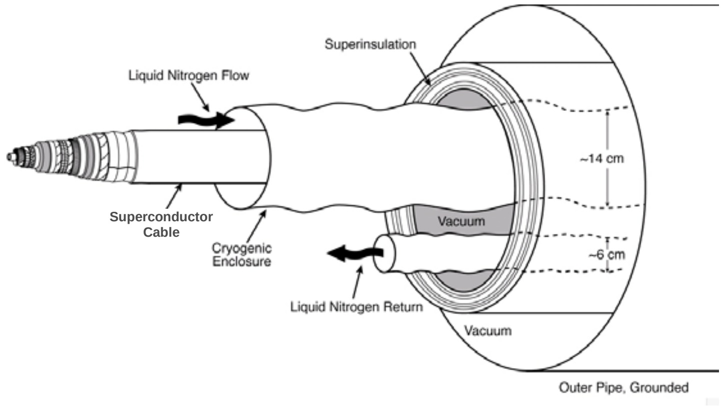


Figure 2: DC superconductor cable concept cross section (Courtesy Electric Power Research Institute)

Figure 3: Typical underground pipeline construction

Superconductor materials must be refrigerated to exhibit their ideal electrical characteristics. For the DC cable so-called high temperature superconductors (HTS) are used, enabling the use of cost effective liquid nitrogen cooling. Cables made with HTS conductors are in service at various locations throughout the world. The cables themselves are placed in a cryogenic enclosure commonly referred to as a cryostat, through which liquid nitrogen flows. See Figure 2. The cryostat is a double walled cylindrical structure that can be either flexible or rigid. The space between the two walls is a vacuum and typically contains layers of super-insulation material. The heat loss in commercially available cryostats for the sizes used in conjunction with superconductor cables are approximately 1.5 W/m. Heat loss is slightly higher at cryostat joints and cable terminations. Significant experience in this area has been accumulated from numerous AC superconductor cable projects.

Once initial cooling is achieved, the refrigeration system must compensate only for the heat loss from the cable system’s insulation system (the cryostat). Since the superconductor cable itself generates no heat, the refrigeration requirements for the DC superconductor cable are independent of both the rating of the cable and the amount of power flowing through the cable. Initial design studies indicate that utilizing refrigeration systems developed for HTS cable systems with Carnot efficiencies over 25% will present an electrical load of approximately 22kW/km. This may be viewed as a fixed “power loss” of the cable, again regardless of the cables' instantaneous or design capacity current rating.

Based on cooling requirements and liquid nitrogen flow characteristics, it is estimated that refrigeration stations would be required approximately every 25km.

2.2 Multi-Terminal DC Transmission

DC power transmission has been used for decades around the world to move large amounts of power from one source of power generation to one load center. While a few multi-terminal systems based on classical line-commutated converter technology have been constructed and placed in operation, the complexity of the control system has limited their deployment. Recently, multi-terminal technology based on voltage-source converters (VSC) has become available. This converter topology provides greater control and flexibility and more simply enables DC lines to incorporate multiple DC terminals.

If the DC line itself is envisioned more as a bus than as a conductor, it is possible to consider the use of multiple DC terminals to function as on-ramps for renewable power sources, and as off-ramps for load centers.

DC terminals employing VSC technology are currently available only at relatively moderate (100-300kV) voltages in comparison to the ultra-high voltages (+/- 800kV) available for conventional line-commutated converter stations. To be used at higher power levels, VSC's lower voltage levels will result in high current levels, where transmission of high current long distances through conventional aluminum or copper conductors will result in considerable resistive losses. The lossless conduction of superconductor power cables provides the ability to carry very high levels of current with no penalty. This removes one design constraint and allows for the consideration of optimizing the voltage rating of the VSC-based DC terminals on cost.

3. TRANSMISSION TECHNOLOGY COMPARISON

DC superconductor cables are not suggested as being optimal for all forms of electric power transmission, but can be seen to be particularly well suited for moving large amounts of power long distances from multiple sources to multiple destinations while addressing various technical and commercial concerns. A comparison of electric power transmission technologies for this specific purpose is detailed below.

3.1 AC Overhead Transmission Lines

The North American power grid is predominately AC, from generators to end users. EHV AC (500 kV and above) is a mature technology and is the accepted and prevailing means today for bulk power transfer. General circuit theory clearly establishes that the higher the AC voltage utilized, the more efficient the power transmission and the greater the distance the power can be carried. As higher voltages are used, there are larger tower and increased right-of-way requirements. These requirements often lead to public objection, which occasionally results in significant delays, modifications, re-routing, or possibly cancellation, of a new line construction project.

From an electrical standpoint, AC overhead lines are governed by various inherent characteristics, which impact the cost-effectiveness of these lines for long-distance, bulk power transmission:

- The further an AC line moves power, the higher electrical losses become.
- The amount of power that can be transmitted decreases with distance.
- When a network of new AC power lines is applied at a voltage higher than the existing system, the existing system may have to be modified or rebuilt in some places to support it.
- It is not possible to precisely control how or where power flows on an AC electrical grid without the use of additional controllers such as flexible AC transmission (FACTS) devices.

3.2 AC Underground Transmission Cables

AC underground transmission cables are widely used and very effective (though relatively expensive) in urban environments to address right of way and visual impact issues. Design of a high voltage underground AC power cable must include consideration of capacitive charging current, conductor heating due to various thermal factors associated with underground placement, and mutual coupling effect from adjacent cable circuits, among other factors. A combination of these characteristics generally limit underground AC cables to relatively short (<100km) distances and modest power levels (≈1,000MW). This precludes the use of this solution for high power, long distance transmission.

3.3 Overhead and Underground Line-Commutated Converter-Based (Point-to-Point) HVDC Transmission

Compared to overhead AC lines, power losses are typically lower for HVDC lines (e.g., 2 instead of 3 conductors). The higher voltages permitted by classical (i.e., line-commutated) converter topology allow for high levels of power (>5000MW) to be transmitted from one point to another. Overhead

HVDC lines, with voltages up to +/- 800kV, have right-of-way requirements similar to those of a single 765kV AC transmission line, and may generally share similar public siting concerns.

Underground HVDC transmission using conventional line-commutated converters has the same advantages of overhead HVDC lines, but with reduced power transfer capacity due to a combination of the voltage rating limitations of HVDC cables and losses. Conventional HVDC cables are not currently available at the highest voltage ratings, which limits power transfer capacity compared to the higher voltage overhead lines.

Of existing technologies, traditional overhead HVDC transmission has the ability to move considerable power over the longest distances with the lowest power losses. However, the point-to-point nature of these lines does not address all the needs for collecting renewable energy from multiple points, nor to delivering to multiple points.

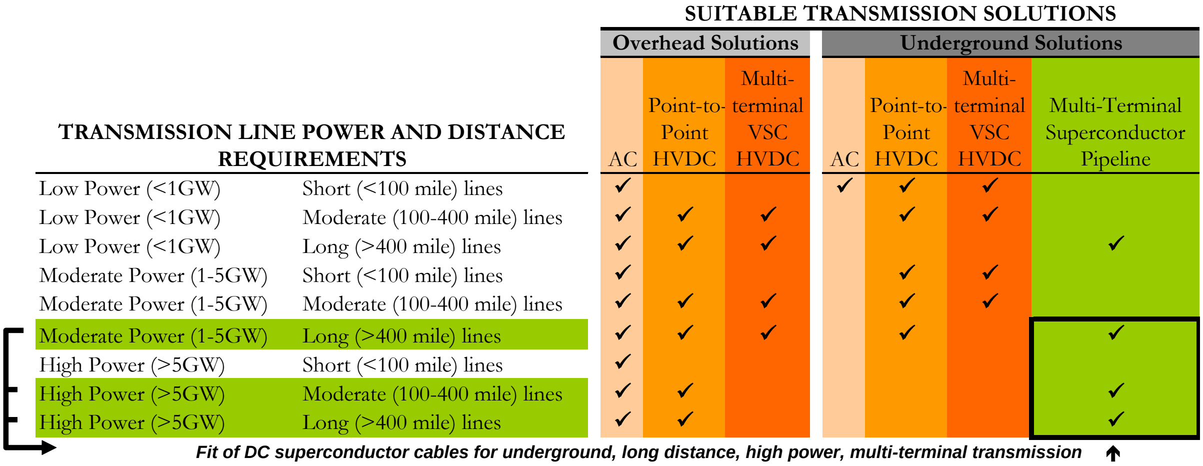
3.4 VSC-based Overhead and Underground HVDC Transmission

VSC terminals have the advantage of enabling multi-drop system but currently operate at lower voltages than do conventional HVDC terminals (typically +/-300kV DC instead of +/-800kV DC). When used with conventional conductors, the lower voltage VSC terminals ultimately place bounds on both the amount of power, which can be effectively transmitted, and the distance the power can be moved. The use of parallel conductors to increase the power handling capacity may result in unacceptably high power losses or excessive conductor heating. As with other technologies, this is more pronounced when moved underground.

3.5 VSC-based DC Superconductor Cables

DC superconductor cable share the reduced right-of-way and low visual impact advantages of conventional underground HVDC transmission lines but extend those advantages to long distances and significantly higher power transfer capabilities with even lower losses. As well, DC superconductor lines are controllable and provide multiple on and off-ramps. However, in contrast with both conventional overhead EHV AC and HVDC, superconductor DC cables have not yet been deployed in utility grid applications and must be considered an emerging technology. As mentioned, a significant number of AC superconductor cables are currently operational in utility grid environments, with lengths under 1 km. While extension of the technology to DC currents and longer lengths is considered straightforward, a development program to obtain and validate in the field optimized engineering of such systems is needed. Advantages of DC superconductor cables are further detailed in the next section.

Table 1 summarizes the various transmission power-distance scenarios and the commonly applied technology for each. Note that for HVDC, back-to-back and underground to overhead transitions in submarine applications are not considered. DC superconductor cables fill a niche for underground, long distance, high power, multi-terminal transmission not presently met by other methods.



TRANSMISSION LINE POWER AND DISTANCE REQUIREMENTS		SUITABLE TRANSMISSION SOLUTIONS: Overhead Solutions			Underground Solutions			
		AC	Point-to-Point HVDC	Multi-terminal VSC HVDC	AC	Point-to-Point HVDC	Multi-terminal VSC HVDC	Multi-Terminal Superconductor Pipeline
Low Power (<1GW)	Short (<100 mile) lines	✓			✓	✓	✓	
Low Power (<1GW)	Moderate (100-400 mile) lines	✓	✓	✓		✓	✓	
Low Power (<1GW)	Long (>400 mile) lines	✓	✓	✓				✓
Moderate Power (1-5GW)	Short (<100 mile) lines	✓				✓	✓	
Moderate Power (1-5GW)	Moderate (100-400 mile) lines	✓	✓	✓		✓	✓	
Moderate Power (1-5GW)	Long (>400 mile) lines	✓	✓	✓		✓		✓
High Power (>5GW)	Short (<100 mile) lines	✓						
High Power (>5GW)	Moderate (100-400 mile) lines	✓	✓					✓
High Power (>5GW)	Long (>400 mile) lines	✓	✓					✓

Fit of DC superconductor cables for underground, long distance, high power, multi-terminal transmission

Table 1: Comparison of transmission methods for different power capacities and distances

4. OPERATIONAL ADVANTAGES OF DC SUPERCONDUCTOR CABLES

4.1 High Power Capacity

Because superconductors have no electrical resistance, two traditional limiting factors to DC transmission related to conductor ampacity rating, namely voltage drop and I^2R losses, disappear. With ampacity no longer an issue, it is possible to construct DC superconductor cables with very high power transmission capabilities even at moderate voltages. This creates the opportunity to deploy VSC-based HVDC terminals with more moderate voltage ratings (e/g., +/- 200kV) at very high power levels. The example used throughout this paper is 5GW (5,000MW), though the construction methods examined indicate that cables with even higher ratings (10GW or more) can be constructed with little to no additional power loss or right-of-way penalty. This essentially unlimited design capability is difficult or even impossible with other types of power transmission.

4.2 Electrical Efficiency

DC superconductor cables themselves have zero I^2R losses as superconductors have zero resistance to DC current flow. Losses in a DC superconductor cable system will be associated with the conversion losses of the AC/DC terminals and the losses of the required cryogenic cooling system. State of the art VSC converter losses are approximately 1% per conversion, or 2% total for the line. As previously, stated in Section 2.1, power consumption of the refrigeration system is estimated at 22kW/km. This is independent of the line's power rating, as no heat will be generated by the superconductor cable itself. This indicates a greater overall electrical efficiency for high power rated lines. For a 1600km, 5GW line, this is approximately 0.7% refrigeration losses or 0.35% for a 10GW line over the same distance. The combined DC terminal and refrigeration losses are roughly one-quarter to one-half that of other point-to-point conventional transmission technologies. See Figure 4.

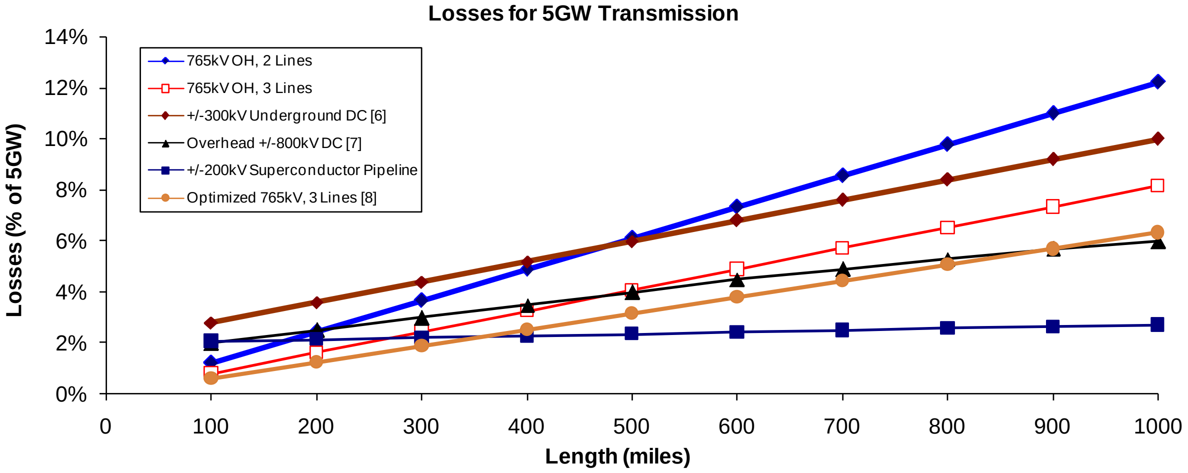


Figure 4: Efficiency of various transmission options[1]

4.3 Simplified Siting and Reduced Right of Way Requirements

Construction of the DC superconductor cable underground addresses significant issues associated with new overhead transmission line construction: public opposition to new high voltage power lines that interrupt the horizon due to their broader right-of-ways, and create various environmental concerns. A recent example of the latter are concerns that overhead transmission towers serve as perches for birds of prey that feed on at risk animal species [11].

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[1] Losses estimated as follows: Overhead 765kV AC, two lines: two lines of 2400MVA SIL using 6-bundle "Tern" conductors with compensation every 200 miles; Overhead 765kV AC, three lines: three lines of 2400MVA SIL using 6-bundle "Tern" conductors with compensation every 200 miles; Superconductor Electricity Pipelines, VSC converter losses of 2% plus 35kw/mile refrigeration losses; others as referenced.

In comparison, DC superconductor cables are highly compact. The original 10GW design concept shown in Figure 2 requires a <1m diameter pipe/cable structure. Conceptual engineering work indicates that cables in the 5-20GW range would all have similar dimensions. This is compared to other technologies whose right-of-way requirements generally scale in proportion to voltage or the number of lines required to achieve a given power rating. Including construction easement, an 8m permanent right-of-way, similar to that of gas pipelines, would be reasonable. Table 2 shows typical right of way required for various types of overhead power lines compared to the DC superconductor cable.

Type of Transmission Line	345kV AC[2]	500kV AC[3]	765kV AC[2][4]	800kV DC[4]	DC superconductor cable
Right-of-Way Requirement	410m	300m	120-180m	80m	8m

Table 2: Transmission line right of way requirements to transmit 5000 MW, 1600 km (1000miles)

The compact nature of DC superconductor cables and their limited right-of-way requirements allows consideration to reuse existing infrastructure rights of way. Railroad tracks, gas pipelines and roadway medians could all accommodate the co-location of DC superconductor cables. While co-location along existing rights-of-way poses its own set of challenges (disruption of the existing service, contingency concerns, etc), the option of co-location, particularly in and around population dense areas, may simplify complex and costly siting procedures.

4.4 Enhanced Grid Operation and Market Dynamics

The precision and flexibility in power collection and delivery provided through a network of superconductor interconnected DC terminals provide opportunities to improve generation integration with the grid by reducing the variability of output from renewable sources (such as wind farms) by aggregating the output of numerous farms.

Additionally, it would be possible for operators of the DC superconductor cables to sell ancillary services [9] such as regulation, spinning reserve, non-spinning reserve and supplemental operating reserve. The DC superconductor cable would also permit two transmission balancing areas to share the variability within each area and therefore reduce the balancing requirements of both, effectively creating larger load balancing areas. The use of one DC line with multiple terminals also provides opportunities to transmit and share power among many generators and consumers across multiple asynchronous systems, as exist in the four electric interconnections in the U.S. and Canada.

4.5 Reduced Impact on Underlying AC Grid

The use of a completely separate superconductor DC transmission cable that supports multiple source and load connections leaves it largely decoupled from the underlying AC transmission network. Faults on the underlying AC power system are isolated from the larger amount of power flowing on the DC cable. The flexibility of DC terminals also permit system operators to determine how the power on the DC cable interacts with the AC system during faults, and may even allow for faster recovery of faults on the AC grid. The use of DC also allows the transfer (so-called “wheeling”) of power long distances across electrical regions without impacting the operation of the regional local grids.

4.6 Underground Security

The prospect of long distance underground transmission addresses various operational concerns with overhead transmission. Overhead transmission lines are subject to damage from a variety of weather-related causes, including ice, snow, lightning, windstorms, hurricanes and tornadoes. As an example, one ice storm in 1998 toppled 1,300 transmission line towers in North America, causing widespread power outages [10]. The time involved to replace or repair that number of transmission towers and bring power back online extends long after the storm has passed.

As with weather-related events, overhead transmission lines are also more susceptible to damage from willful attack. Overhead transmission lines and towers are easier to locate and are more vulnerable to a variety of methods of attack. The underground nature of DC superconductor cable would make them harder to locate, more difficult to damage and easier to harden against attack. The latter could be accomplished with more damage-resistant external cable shielding, or simply through deeper burial of the cable itself.

4.7 Redundancy Considerations

While carrying gigawatts of power over a single superconductor DC cable raises questions about system security, redundancy can be provided by multiple parallel branches or a loop network concept as shown in Figure 5. This is similar to what would typically be proposed on a high voltage overhead AC network. Overall system architecture is important in any cable system since, while power outages are much less frequent, underground construction does result in lengthier repair times. Refrigeration system reliability would be addressed in a manner similar to what is done on existing AC superconductor cable installations; redundant cooling systems, redundant power supplies to the cooling systems, and provision of reserve capacity to provide additional cooling to compensate for the loss of one or more units along the route.

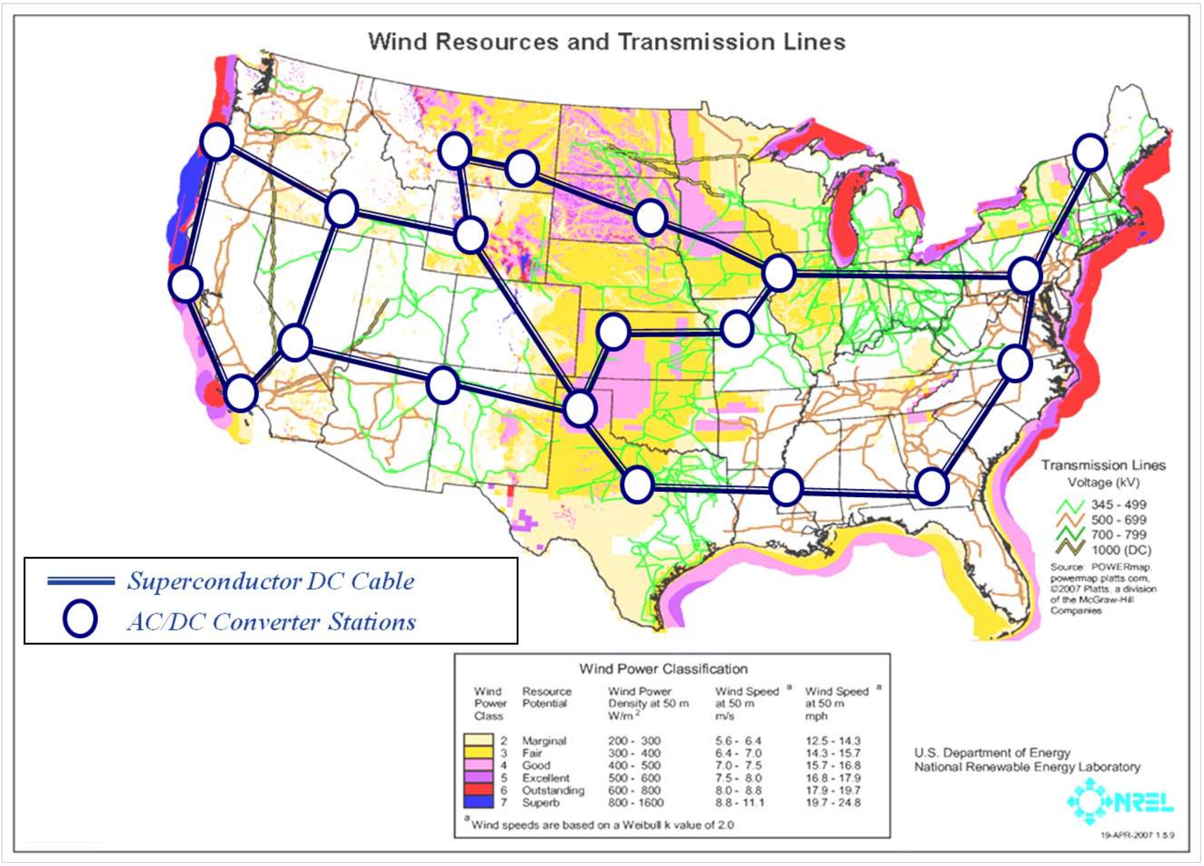

Figure 5: Possible U.S.-wide network of superconductor DC cables and HVDC converter stations

5. COST COMPETITIVENESS

For a 5GW, 1,600 km (1000 mile) cable system, it is estimated that the cost of a DC superconductor cable would be in the range of US$8 - $13 million per mile fully installed. This mature system cost including appropriate contingencies to allow for the preliminary, conceptual level of design was based on analysis and adaptation of a conceptual design developed by the Electric Power Research Institute [12], cable, cryogenic refrigeration, DC terminal, and engineering costs from past proprietary project work, supplier quotations, and contemporary right of way and installation cost data[13], [14]. Redundant cooling systems are included in the estimate. This computation was based upon a detailed design study of a +/- 200kV superconductor cable and use of matching voltage VSC-based HVDC converter. The estimates include the cost of seven sets of 750MW DC converter stations, the largest presently available. The low end of this estimate is based on a single 5,000 MW cable system while the upper end is based on a fully redundant 5,000 MW system (two cables). Note the cost is similar to the $7 to $10 million cost per mile estimate of two or three overhead EHV lines complete with the substations [15] that would be required to carry the equivalent power over the same distance. At least one regulatory filing suggests this estimated EHV line cost may be low, reflecting a $5.5 million per mile cost for a single line [16]. Costs for EHV lines do not include investments that may be required to upgrade the underlying transmission infrastructure to support any type of EHV AC line overlay. Some upgrades may also be necessary for DC superconductor cables but are not anticipated to be as extensive as those required for an AC overlay.

Conventional point-to-point overhead UHVDC transmission line costs are generally estimated at $5 million per mile. Though less expensive on a per mile basis, they presently do not support distributed on- and off-ramp capability, have higher losses, and share the greater right of way requirements, of overhead AC lines.

As with all DC options, DC superconductor cables become more cost competitive the longer the distance as the DC converters are largely a fixed cost based on the total MW power rating of the converters, and are not affected by line length.

The cost breakdown of a DC superconductor cable varies with the line length and DC converter ratings. Generally, the cable length and associated costs such as refrigeration, installation, and right-of-way, vary with the line length. DC converter costs are based on total MW rating and are independent of line length. Figure 6 shows the estimated cost breakdown of a 5000MW, 1000 mile, DC superconductor cable.

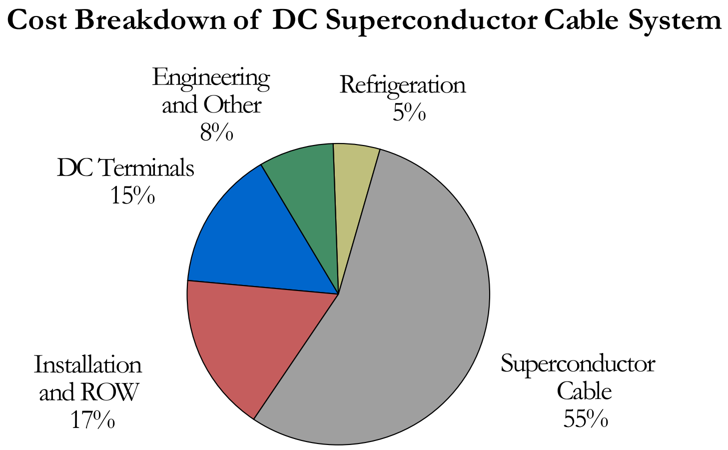

Figure 6: Cost Analysis of a 5000 MW, 1000 mile, DC superconductor cable

For conventional transmission technologies, the cost of building underground transmission is generally considered to be higher than overhead, particularly for lower voltage transmission systems. This is primarily due to the cost of construction and permitting in high cost urban areas. By comparison, the distance traversed by DC superconductor cables will result in significant lengths being installed in cross-country environments, where lower construction costs will prevail. It should be noted that even for conventional transmission technologies, at the power levels being considered, the difference in costs between overhead and underground lines diminishes significantly.

Doubling the example to a 10,000 MW, 1000 mile application only increases the cost by one-third, and the losses drop to 2.4%. This demonstrates the cost effective nature of transmitting large amounts of power via DC superconductor cables.

6. SUMMARY

DC superconductor cables offer a new option for high power, long distance transmission of electric power. This efficient solution is shown to be cost competitive with currently available options while offering the security and siting advantages of a compact underground cable. When coupled with multiple VSC terminals and applied at ratings over a few GW and lengths over a few 100 km, DC superconductor cables offer an attractive transmission option for connecting diffuse sources of renewable power to remote load centers in a controlled manner.

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