Programme Area: Energy Storage and Distribution

Project: Network Capacity

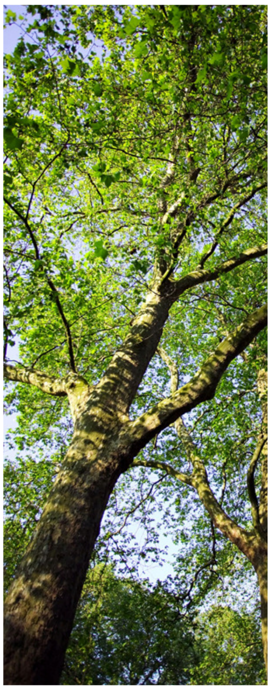
Title: Barriers to Application of Multi-Terminal HVDC in the UK

Abstract:

The report assesses both technical and non-technical barriers to the deployment of MTHVDC in the UK transmission system.

Context:

The Network Capacity research project identified and assessed new technology solutions that could enhance transmission and distribution capacity in the UK. It assessed the feasibility and quantified the benefits of using innovative approaches and novel technologies to provide improved management of power flows and increased capacity, enabling the deployment of low carbon energy sources in the UK. The project was undertaken by the management, engineering and development consultancy Mott MacDonald and completed in 2010.

The ETI Energy Storage and Distribution Programme - Network Capacity Project

Work Package 2 Task 4 Final Report
Technical and Non-Technical Barriers to Application of Multi-Terminal HVDC Transmission to UK Grid

August 2010
The Energy Technologies Institute (ETI)

Mott MacDonald

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The Energy Technologies Institute (ETI)

Holywell Building, Holywell Park, Loughborough, LE11 3UZ

Mott MacDonald, 1 Atlantic Quay, Broomielaw, Glasgow G2 8JB, United Kingdom
T +44(0) 141 222 4500   F +44(0) 141 221 2048, www.mottmac.com

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Mott MacDonald, 1 Atlantic Quay, Broomielaw, Glasgow G2 8JB, United Kingdom
T +44(0) 141 222 4500 F +44(0) 141 221 2048 W www.mottmac.com

Content

1. Summary

1.1 Background

Mott MacDonald has been commissioned by the Energy Technologies Institute (ETI) to carry out the ETI's Network Capacity Project. This project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals. Specifically the project will assess the feasibility of two potential areas of development to improve the operation and increase the capacity of the UK onshore T&D systems. The outcome will be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

- The first area of the project is focussed on the feasibility of applying new and existing power electronic technologies to provide enhanced management of network power flows in order to release more capacity within the T&D system.
- The second area concentrates on the technical feasibility of multi-terminal HVDC in the context of operation within the existing UK T&D system.

The work associated with both areas comprises an assessment of the credible options from these technologies in the context of power flow management including the benefits and also associated impediments to their development and deployment, and will provide guidance in respect of technology development opportunities. The work has been structured into two packages;

- Work Package 1 concentrates on the novel technologies with the potential to release capacity in the UK T&D networks. The work in this package comprises a literature review and modelling of the various technologies integrated into the networks to determine their effectiveness and requirements for such integration. It will also include analysis of environmental and social impacts, and of the barriers to development and deployment.
- Work Package 2 concentrates on the use of multi-terminal HVDC transmission and its integration within the existing UK T&D networks. The work in this package will comprise a feasibility assessment and detailed modelling of multi-terminal HVDC to assess its performance, impact and potential interactions arising from its use. It will also include analysis of the requirements for such integration, the benefits case for conversion of existing AC lines, and of the barriers to development and deployment.

1.2 Work Package 2 Task 4 Final Report

Mott MacDonald commissioned Manitoba HVDC Research Centre (Manitoba) to carry out an assessment of the technical and non-technical barriers to the application of multi-terminal HVDC to the UK's transmission grid as covered by the Work Package 2 Task 4 scope of work. The final report received from Manitoba is included as Appendix A. It incorporates amendments to the report that have been made in response to ETI comments received on the draft report submitted in April 2010.

The report is provided as a separate stand-alone document at this stage. The final report for the project consolidates and updates the outputs from each of the individual task reports, including that covered by this report, in order to provide a coherent output that represents the integrated output from all of the work carried out.

Appendices

Appendix A. Manitoba HVDC Research Centre. Supply Chain Issues and Barriers to the Application of Multi-terminal HVDC Transmission to the UK Transmission Grid

Report

Engineering Support Services for:

ETI PROJECT –WP2 TASK 4 – SUPPLY CHAIN ISSUES AND BARRIERS TO THE APPLICATION OF MULTI-TERMINAL HVDC TRANSMISSION TO THE UK TRANSMISSION GRID

Client: Mott McDonald

Manitoba Hydro International Ltd.
211 Commerce Drive
Winnipeg, MB R3P 1A3
CANADA
www.pscad.com

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3	Revised	April 20, 2010
4	Revised in line with ETI comments	July 30 2010

Contents

1. Introduction

The Energy Technologies Institute (ETI) identified the need from important engineering studies to assess innovative approaches and technology solutions that could lead either:

- to the enhancement of the capacity of the existing onshore UK electricity transmission and distribution networks, or
- to the expansion of these networks by means other than the construction of new overhead line infrastructure,

and thereby enable the installation of substantially more renewable energy systems in the UK than the current T&D system can accommodate.

The project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals. The outcome is to be a thorough and well presented analysis that will enable the ETI to make informed decisions as to where future work in the program should be directed.

1.1. Project Structure

Work Package 2 concentrates on the feasibility of multi-terminal HVDC in the UK Transmission network. The work comprises of a literature review and modeling of the various HVDC Technologies integrated into the existing UK AC transmission network to determine the HVDC System performance and integration requirements. It also includes analysis of environmental and social impacts, technical and non-technical barriers, and supply chain issues.

Task 4 in Work Package 2 is to assess:

- The technical and non-technical barriers that could prevent or limit the deployment of onshore multi-terminal HVDC networks in the UK, and provide potential solutions to these issues including, where possible, investment requirements.
- The potential supply chain issues relating to multi-terminal HVDC systems, including a cost estimate of the multi-terminal HVDC link. The objective is to identify where supply chain issues present problems to potentially useful multi-terminal HVDC links technology and recommend how these issues would best be addressed.

This report is the deliverable for Task 4 of Work Package 2 and it briefly describes the assessment process used and draws conclusions concerning the barriers and supply chain issues. Task 1 is to assess the feasibility of developing onshore multi-terminal HVDC in the UK including the benefits to the conversion of AC overhead lines to HVDC operation. Task 2 is to model and assess the performance of the onshore multi-terminal HVDC systems integrated into the existing UK AC T&D network and associated security supply issues. Task 3 is to evaluate the impact of new onshore multi-terminal HVDC systems in the UK.

The technologies associated with HVDC Transmission have been changing rapidly resulting in a number of different HVDC Transmission alternative technologies becoming commercially available.

1.2. Task Methodology

The approach taken in this task was to research papers written, contact suppliers, review associated web sites, extract information from past conferences and review, discussions with other HVDC experts. There will be a workshop to be held May 12th, 2010 in London, UK to discuss the technology options, benefits and, barriers and solutions which should be incorporated into the final report.

The field of power electronics of which HVDC is one technology has been growing rapidly with increases in device ratings, and development of new converter topologies and switching strategies. As a result of this development, the high performance devices of yesterday have been replaced with even higher performing devices today; which of course makes published articles out of date. Thus one of the task difficulties is to extract only information that is relevant today. Also other technologies which use power electronics could have an impact on the supply chain, barriers and solutions and will be highlighted here as well.

The University of Strathclyde (UoS) is reviewing the current state of the art of new and emerging technologies of which HVDC technology is one. This report should be viewed in conjunction with the UoS report. This report includes other work done in WP 2.

This report will present the barriers to the usage of HVDC Transmission in the UK and discuss how the barriers were initially formed and how technological advances have changed, mitigated or removed some of these barriers. The solutions to the barriers and supply chain issues depend on an understanding of how these technological advances could be better utilized; as increased usage could be a supply chain issue.

Four types of HVDC Transmission technologies which will be discussed are:

1. Line Commutated Converters (LCC) – This is the original form of HVDC Transmission which uses Thyristors to convert AC current to DC current at one converter station and DC current to AC current at the other station in general. LCC belongs to the Current Source Converter family.
2. Capacitive Commutated Converters (CCC) – This is a version of a LCC where a series capacitor has been placed between the converter transformer and the Thyristor Valves at the converter station to provide the reactive power required by the DC conversion process. CCC belongs to the Current Source Converter family.
3. Voltage Source Converters (VSC) – Two-level – This is a relatively new HVDC technology which uses IGBTs switched at high frequencies in the 0.5 to 3.0 kHz range with large stepped voltages to control both real and reactive power at the

same time. It can be used in conjunction with LCCs or by itself to form Multi-Terminal HVDC Systems. This is produced by ABB and is known by the name HVDC Light.

4. Voltage Source Converters (VSC) – Multi-level - This is a version of a two level VSC which switches the IGBTs on in sequence for an AC waveform producing much smaller stepped voltages and thus much lower losses. It is produced by Siemens and is known by the name HVDC Plus.

Note: A STATCOM is a part of the VSC family but will not be discussed in this report as it is addressed as part of Work Package 1.

2. Technical Barriers

Technical decisions are usually influenced by economic and commercial considerations and will therefore be included in the discussion of technical barriers.

There are no real technical barriers associated with the slowness the power reversal in HVDC itself. The converter stations themselves can reverse power virtually instantaneously. The problems come from other aspects. A Line Commutated Converter (LCC) is usually used to transmit bulk power over long distances. Depending on the length of line; it can take tens of milliseconds to discharge the energy stored in a transmission line before the power reversal can take effect. For a back to back LCC link where there is no transmission line the power reversal can happen virtually instantaneously. A LCC consumes large amounts of reactive power which are provided from the AC filter banks, shunt capacitors, synchronous condensers or from the grid itself. The reactive power could be supplied from fast acting FACTS devices allowing for fast power reversal but this is more expensive. Thus this is a commercial barrier not technical. Thus power changes must be implemented slowly to allow the correct amount of reactive power to be supplied from these sources. A Voltage Source Converter controls both real and reactive power and thus is better suited for power reversal and multi-terminal operation.

2.1. Line Commutated Converters (LCC)

The first HVDC link was a LCC which used an undersea cable to connect the Island of Gotland to the Swedish mainland in 1954. There are now two LCC-type HVDC undersea cables in the UK. One is the Cross Channel link between France and England and the other is the Moyle Interconnector between Northern Ireland and Scotland. England was an early adopter of HVDC – LCC technology with the cross channel link between England and France completed in 1961.

A new HVDC –LCC link (1 000 MW) called Britned between England and the Netherlands is under construction and is scheduled for completion in 2010

The LCC type HVDC technology is now feasible (one Bipole in-service in 2009) at +/- 800 kV and 6 000 to 8 000 MW's which is likely beyond the needs of that required in the UK. Also this study is to not consider new lines but the adoption of existing lines so a more limited power transfer level would be considered.

2.2. Voltage Source Converters (VSC)

Because VSCs are so new and developing rapidly information available in published article may be limited or hard to find so they are presented here in more detail. It is necessary to understand the advantages of these technologies as there are barriers to accessing these benefits.

VSCs are self commutating and so do not require any synchronization to the network frequency. A VSC has the same objectives as a LCC-HVDC converter which is to convert AC to DC or vice versa. VSC started at lower powers and voltages in the industrial and transportation sectors and has been used there for many years. It is a relatively new HVDC technology made possible by the development of high voltage and high power IGBT's. The IGBT's are switched at high frequencies in the 0.5 to 3.0 kHz range to control both real and reactive power at the same time. There are now ten schemes in operation and four under construction. Because it is so new, it is relatively unknown, not well understood and is considered "unproven" as only HVDC Schemes with relatively small power levels and lower voltages have been constructed to date. This is a major barrier in the knowledge, understanding and acceptance of this new and promising technology.

A VSC can produce a sinusoidal voltage at its AC terminals without any AC network present. The two level topology VSC was developed by ABB and is called HVDC Light. Another topology, called Neutral Point Clamped (NPC), was developed by ABB but is no longer produced and will therefore not be discussed further.

There are a number of major benefits with the use of VSC as outlined below:

- Controls both active and reactive power, eliminating the need for additional reactive compensation.
- Little or no harmonic filtering requirements.
- Simpler transformers with no DC bias and star and delta windings.
- Operation down to an Effective Short Circuit Ratio (ESCR) of zero. No synchronous compensators required to supply reactive power and increase short circuit levels.
- No commutation failures
- Multi-terminal configurations are a simple topology. VSCs can be used in conjunction with LCC's or by themselves to form Multi-Terminal HVDC Systems. The number of nodes is potentially unlimited but there will some practical considerations.
- Can be used to supply a load or to "Black Start" a station.
- Can be used for cable systems and overhead lines i.e. Caprivi (+350 kV 300 MW) is the first overhead line under construction, with an in-service date of 2010.
- Compact Dimensions - 50 % of the station footprint as compared to a conventional LCC.

- Power reversal by adjusting the DC voltage at each converter station, reversing the direction of the current. Because there is no voltage polarity reversal it enables the use of lower cost polymeric cables (XLPE).
- Continuous variable power - full in one direction to zero to full power in the other direction.

There are also some disadvantages with VSC – Two-level topology as follows:

- Higher losses with the VSC – Two-level topology of approximately 1.5% per converter station. Siemens also indicates that the losses for the multi-level VSC topology are closer to the conventional LCC losses.
- Limited voltages and powers at present. ABB indicates that they can provide
- +/- 320 kV at 1 200 MW. Siemens indicates that they can provide up to 1 500 MW with their multi-level VSC topology.
- Lost cost polymeric cables (XLPE) have only been developed up to 325 kV, but none are in-service to date.
- Unable to clear line faults. For a point to point system the AC side breakers must be tripped to clear the DC fault. Also for multi-terminal schemes a fast operating DC breaker must be developed and both ABB and Siemens are actively pursuing this development.

The list of disadvantages will eventually decrease over time. Siemens has already developed a VSC with a multi-level topology with lower losses approaching that of a LCC. The switching losses are substantially less as each IGBT is switched on and off only once sequentially and the level of the voltage transient is only the level of the IGBT. With the two-level topology the IGBT's are switched on and off hundreds or thousands of times each A.C. cycle (50 Hz)resulting in the higher losses of about 1.5%. The multi-level topology is closer to that of an LCC according to the Siemens web site but no numerical figure is given.

Both ABB and Siemens are actively developing a DC breaker. ABB developed a similar breaker which diverts the current from an electrode line into a metallic return path when in monopolar operation at Sylmar Converter Station in Los Angeles California, USA. This design format will likely form the basis of the technology to develop the DC breaker, so it is anticipated that a DC breaker will be forthcoming in a couple of years. AREVA (now Alstom) has taken a different approach with replacing the diode with a controllable element such as a thyristor or IGBT enabling the valve to clear the fault, thus there is no need for a DC breaker. However there is the higher cost of the Valve versus the cost of the DC breaker.

2.3. Converting AC Transmission lines to DC Transmission

It would be possible to convert one or more of the existing AC Transmission Lines to DC Transmission Lines. For more details and other relevant technical data see the report from TGS [3] from WP2 Task 1. There are a number of potential barriers to converting AC Transmission line to DC Transmission lines.

Firstly there is the outage costs and outage time required to the AC Transmission Line during the crossover to the DC Converter Station and subsequent system testing. Secondly there is the physical size of the converter station for the LCC-type HVDC. The existing AC Substation would have to be expanded to accommodate the DC equipment. Property would have to be acquired from existing landowners adjacent to the existing AC Substation. Thirdly there is the high cost of the converter stations themselves as indicated in section 4 below. Both the DC magnetic field and electric field are less than for an AC transmission line. While it would have to be studied, this would likely not be a barrier.

2.4. Underground DC Transmission

It is becoming less acceptable to have overhead transmission lines of any kind, so one option is to go underground. There are two underground SVC - HVDC Transmission links in-service in Australia to date. One is the Murray link at +/- 80 kV, 180 MW, 65 km and the other is the Direct link at +/- 150 kV, 200 MW, 180 km. There are no LCC – HVDC Transmission links that are entire underground but portions of some links are underground. An example of the is the NorNed link (750 MW) between Norway and the Netherlands.

It is possible to install a HVDC underground link in the UK at +/- 500 kV, 1 500 A and 1 500 MW. It would likely be LCC technology with a Mass Impregnated cable [4]. Barriers again are the large physical size of the converter station and its cost. In addition there is the much higher cost of the type of cable which must be used with an LCC converter. The cable length at present could be another barrier. In theory there should be no limit to the number of 500 to 1000 m sections that could be joined together. For more details and other relevant technical data see the report from TGS [4] from WP2 Task 1.

An alternative option would be to use a Voltage Source Converter, presently limited to 1 500 MW with the Siemens Multi-level converter and 1 200 MW with the ABB two-level converter for the converters themselves, but they are further limited by the rating of the underground cables. Additional barriers would be a considerable risk as VSCs presently under construction are only in the 300 MW to 400 MW range. While the VSC can use the higher cost Mass Impregnated cable or oil filled cable the lower cost XLPE cable is only capable of 325 kV and 1 500 A at present. This would limit the VSC to +/- 325 kV, 1 500 A, 975 MW. While the station size is much smaller compared to the LCC it is still costly. The DC magnetic field is less than for an AC underground transmission. While it would have to be studied, this would likely not be a barrier.

Another alternative would be to lay several pairs of DC cables to increase the transmitted power and link availability. However with the high cost of cables the project may not be economically feasible.

2.5 Multi-terminal LCC
The number of terminals that can be used for current source converters is limited to 3 to 4 terminals depending on their location with respect to each other and AC system constraints. Hydro Quebec had built a HVDC system for 5 terminals but found that they could only operate 3 of them properly. Hydro Quebec has not released details as to why they limit the operation to three terminals. The other two terminals were relatively small and seldom used. An AC system disturbance at one of these stations would cause it to commutation fail. This would create a disturbance at the other four stations which became unacceptable. Manitoba Hydro operated 4 terminals on one DC Transmission line for a few days in 1996 without any problems. In Manitoba a section of both of the two HVDC Transmission lines was destroyed in a wind storm and all four terminals were operated on one DC Transmission line until the other was restored. There are several other three terminal DC schemes in the world such that three terminal operation of LCC HVDC is quite feasible. This is based on experience not theory.

2.5. Multi-terminal VSC

In theory Multi-terminal VSC appears to have some potential advantages in integrating renewable resources into the AC grid. The number of terminals is potentially unlimited and DC is an efficient way of transmitting power.

VSCs are still in their infancy and not proven at higher power levels. No multi-terminal VSC links have been built to date. The high cost of the terminals has to be offset by other equipment savings such as that which would be necessary otherwise for supplying reactive power, and by the increased efficiencies. As AC Transmission lines are pushed towards their thermal limits; they require more reactive power. This may make VSCs become more competitive overall. However, barriers exist for the conversion of existing AC transmission lines to DC transmission, including outage costs during construction, substation expansion and associated cost of land, as well as other issues as outlined in section 2.3 above.

2.6 HVDC Circuit Breakers

Multi-terminal HVDC using VSCs requires the development of Fast Acting DC breakers as VSCs are unable to clear DC transmission line faults. Direct Current has no natural current zero as Alternating Current does, thus it is not possible to extinguish the arc in a circuit breaker. Thus to make a DC circuit breaker it is necessary to introduce a current zero into the direct current. To accomplish this it is necessary to add an oscillator circuit to the circuit breaker in the form of an inductance and capacitance. Thus you have a Direct Current with an Alternating Current superimposed on top of it and a current zero. Also a way to speed up the tripping time to make it fast acting is required.

ABB developed a so called “DC Breaker” to commutate the current from the electrode line into the other conductor in case of monopolar operation so no DC current would flow into the ground. This was not a true DC breaker as it only commutated the current into another current path and did not actually interrupt it. A so called “DC Breaker” was installed in the Sylmar Converter Station in Los Angeles California.

A LCC does not require a DC Breaker as it can force the current to zero and the breaker can open and clear the DC transmission line fault.

2.7 Multi-terminal VSCs and Wind Farms

The cost of the VSC stations is high and with multi-terminal VSCs there are more stations compounding the problem. The suppliers of VSCs are actively pursuing a reduction in the cost of the VSC stations themselves to mitigate this cost barrier. Another way to mitigate this cost barrier and make VSC’s more affordable would be to increase the power output and potential revenue from the wind farm itself.

While the wind farms themselves are outside the scope of this report, a high level description of how this might work has been provided below.

It is theoretically possible to obtain up to 50% more power [5] from a wind farm, improve power quality and increase wind generator reliability and availability by using VSC technology. Also the wind farm would then not contribute to an increasing short circuit level and it would provide its own reactive or provide reactive power to the grid if needed on an instantaneous basis. Wind power has to be injected into an AC grid at 50Hz. The wind turbine rotates at a speed of 20 to 50 rpm thus a gearbox is employed to increase this to 1500 rpm for the generator. As the air speed power exceeds the turbine power capability two commonly used methods to control this are used. One is changing the pitch angle and the other is a stall cut out technique at about 25 m/sec utilizing blade design. Both these methods introduce inefficiencies into the generation process. Also wind fluctuations at higher wind speed introduce fluctuations in the generated power and thus power quality issues.

It is possible to use a variable speed wind generator and connect it to the grid via a VSC. No gearbox would be required and as the gearbox is mechanical; its removal could potentially improve the reliability and availability. Power fluctuations could be more easily managed and up to an increase in power of 50% is theoretically possible depending on the wind speed and variability at a given site. The actual increase in power is likely to be smaller.

2.8 Reliability:

Reliability for SVC – HVDC topology does not appear to be a barrier to its adoption. However reliability figures are based on VSC HVDC systems that have not been in-service for long periods yet. ABB’s figures are:

Forced outage rate	1 - 2 per year
Forced unavailability	0.3 -0.5 % per year
Scheduled unavailability	less than 0.4% per year
Availability	greater than 99%

These figures compare very well with LCC – HVDC topology.

2.9 System Interactions

HVDC Systems are unlikely to cause interactions with the AC system equipment if they are designed properly. The systems have to be modelled properly and getting data from third parties can be difficult.

3. Non-technical Barriers:

One of the non-technical barriers is the lack of a good concise reference source dealing with the major aspect of the various HVDC technologies. There are a lot of articles and a number of books dealing with HVDC so at first glance it would appear that HVDC is well represented.

- Many articles that are written use reference material from previous articles. In some instances a barrier from a previous technology is assumed to exist in the newer HVDC technology. An example of this follows. The Mercury Arc Valves required a minimum current of approximately 10% could not operate at firing angles approaching 90°. This is not a limitation for Thyristor Valves as they can operate at 90 ° which results in the voltage being zero; so no power is transmitted. This has been implemented in the Lamar project is the USA. This does create higher losses when operating at zero power and the Thyristor Valve is more expensive as the damping circuit is required to have a higher capacity for continuous operation. However the minimum current restrictions required for Mercury Arc Valves, is not applicable to Thyristors text books continue to specify a minimum current requirement.
- Another example is the requirement for large AC Filters to provide reactive power to the HVDC Converters. The reactive power requirements can be provide from many different sources such as the AC system itself (most HVDC Systems are designed to be reactive power self sufficient), capacitor banks, synchronous condensers or from the HVDC system itself as in the case of Capacitor Coupled Converters (CCC) or Voltage Source Converters. In most instances large AC filters were an economic way of providing the reactive power requirements. As no reactive power was required by the DC Filters and the harmonic currents were only in the 10 Ampere range; these have for some time now provided by “active” filters. An active filter measures a harmonic voltage or current and produces a wave shape equal and opposite to the harmonic effectively cancelling it out. As the power electronics developed additional capacity it was applied to the AC Filters that required larger currents in the hundreds of Amperes range. An example of this is the Neptune project in Long Island, New York, USA where uses active filters as the reactive power is provided by other means.
- Voltage Source Converter’s (VSC) are the newest addition to the HVDC technologies. They produce both active and reactive power. This technology has

been advancing so rapidly that technical articles cannot keep up with the advances and published articles rapidly become obsolete.

A second non-technical barrier to the adoption of new HVDC technologies is the process of "change" itself. At a personal level if change comes from within, it is self motivating and generally accepted. If change is imposed on a person the result is usually completely different. It can cause anxiety, depression and anger before moving on to acceptance and embracement however some people never move on to acceptance. These personal barriers to change are also manifested by organizations.

4. Costs Associated with Multi-terminal HVDC Links [1]

The cost associated with multi-terminal HVDC links depends on the power transmitted and the length of the transmission line so the numbers quoted below are indicators only. Also prices are volatile based on commodity prices for materials such as copper and of course supply and demand for the HVDC. Demand right now (April 2010) is high for HVDC Systems. Costs are based on a full turnkey project of the Engineer, Procure, and Construct (EPC) type. At this stage only typical costs are given. For comparison purposes, an HVDC link of 600 km length has been used.

A conversion rate of $ 1.58 CAD = 1.0 Great Briton Pound (GBP) was used. The costs are presented in both CAD and GBP. The GBP costs are rounded to two significant figures.

The costs presented below are for new construction only and do not apply for conversion of existing AC Transmission Lines.

4.1. Costs of Multi-terminal Current Source Converters

The estimated cost for +/- 500 kV 3 000 MW *overhead transmission line* is 480 000 GBP ($ 762 000 CAD) per km. The transmission line is assumed to be a latticed steel self supporting structure carrying two bundled conductors. Each Bundled conductor consists of two sub-conductors. One shield wire is installed on top of each tower. Transmission line losses are approximately 1.2% per 100 km.

The EPC cost for *each converter station* for +/- 500 kV 3 000 MW LCC as a true (two separate conductors) Bipole overhead transmission line scheme is estimated to be 210 Million GBP ($330 Million CAD).

Thus the EPC cost of a three terminal +/- 500 kV 3 000 MW with 600 km of *overhead DC transmission link* is estimated to be 910 Million GBP ($ 1 447 Million CAD).

Note: The EPC cost for *each converter station* for a +/- 500 kV 2 000 MW LCC as a true (two separate conductors) Bipole overhead transmission line scheme is estimated to be 160 Million GBP ($250 Million CAD).

4.2. Costs for Multi-terminal Voltage Source Converters

In the case of VSCs no multi-terminal links have been constructed; therefore there very little information is available. VSC's are potentially ideally suited for multi-terminal operation and the number of terminals is potentially unlimited, but there will be practical limits. The VSC links that are in-service have a fairly small in capacity. Several are under construction in the 300 to 400 MW range, therefore no actual costs exist only estimates. The technology is advancing rapidly and the suppliers advise they can produce 1 200 MW (ABB) and 1 500 MW (Siemens) but no costs are currently available for these higher capacities.

Another barrier is that DC circuit breakers will be required for multi-terminal VSC operation and must be developed. The estimated cost is about 0.63 Million GBP ($ 1.0 Million CAD) per breaker and it is anticipated that a DC breaker will be available in the near to medium future.

4.2.1. Overhead Transmission Lines

No VSC – HVDC Links have been constructed using overhead transmission lines there for no actual costs are available. However costs have been estimated for some of the schemes under construction such as the Caprivi HVDC Link; so this is the best information available at this time.

The estimated cost +/- 200 kV, 600 MW *overhead transmission line* is 375 000 GBP ($ 592 000 CAD) per km. The transmission line is assumed to be a latticed steel self supporting structure carrying two bundled conductors. Each Bundled conductor consists of two sub-conductors. One shield wire is installed on top of each tower. Transmission line losses are approximately 1.3% per 100 km.

The EPC cost for *each converter station* +/- 200 kV, 600 MW VSC as a true (two separate conductors) Bipole overhead transmission line scheme is estimated to be 80 Million GBP ($125 Million CAD).

Therefore the EPC cost of a three terminal +/- 200 kV 600 MW with 600 km of *overhead DC transmission link* is estimated to be 460 Million GBP ($ 730 Million CAD).

4.2.2. Underground transmission cable (XLPE)

XLPE Cable is a lot less expensive than mass impregnated cable and other cables types however the cable can only be used up to 325 kV and approximately 1 500 Amperes for DC applications at present. The power is therefore limited to 975 MW for a Bipolar System. In earlier installations the XLPE cable was previously limited to 200 kV, thus the costs are only available at the 200 kV level at this time.

The estimated cost +/- 200 kV 400 MW *underground transmission cable* is 272 000 GBP ($ 430 000 CAD) per km.

The EPC cost for *each converter station* +/- 200 kV, 400 MW VSC as a true (two separate cables) Bipole underground transmission cable scheme is estimated to be 54 Million GBP ($85 Million CAD).

The EPC cost of a three terminal +/- 200 kV 400 MW with 100 km of *underground DC transmission cable link* is therefore estimated to be 130 Million GBP ($ 213 Million CAD).

5. Environmental Concerns

The large size of the current source converter stations is a concern as they use up valuable land resources. There is also the issue of pollutants such as oil from transformer in the station getting into the environment. While this is no different from an AC Substation; the larger size makes this concern more visible to the public. This is of course a bigger issue in England because of the population density than it would be in less populated countries. VSCs occupy a much small footprint, so are less of a concern.

Another concern is earth currents during mono-polar operation. In a Bipolar HVDC Scheme if one pole trips the remaining pole can be kept in-service but the current must return via the ground or the other conductor or via a dedicated separate conductor. Putting DC currents into the earth raises concerns about corrosion with home owners, railways, pipelines etc. While Geomagnetically Induced Currents (GICs) exist in the ground due to sun spot activity and must be catered for anyway, this should not be a concern. As GICs are not common knowledge DC current from the converter station will still be a concern. To mitigate the ground current, a dedicated conductor can be added at low voltage but this will increase the cost of the project.

Other environmental concerns are ground heating (only for cables), electromagnetic fields (EMF) and noise. Acoustic noise levels in the 40 to 45 dB (A) range can be achieved at the station boundary. The other levels are at or lower than equivalent AC underground cables. The EMF for overhead HVDC Transmission is less than the comparable AC transmission.

6. Supply Chain Issues

The HVDC Technologies are part of the power electronics family as they use the high power Thyristors as building blocks for the Thyristor Valves. They use many of the same components as AC Transmission does and therefore delivery dates and shortages may be compounded.

For many years there was very little interest in HVDC transmission and the suppliers shut down or planned to shut down some of their manufacturing facilities. AREVA for example shut down their transformer plant near Paris France.

6.1. Increasing World Wide Demand

In the last 5 years, the benefits of HVDC have become more appreciated worldwide. World demand for electricity has increased with some countries seeing increases in the order of 8% per year. China for example built 90 000 MW of new generation in one year alone and GDP is still above 10% per year.

As a result of concerns about the risk of CO^2 emissions leading to Climate Change, many countries or areas of countries have embraced the aspect of providing some this increased demand using renewable technologies such as wind, solar, tidal etc. Also the licenses for many existing coal and oil fired plants and nuclear plants will expire, they are not being renewed and alternate generation sources must be found. Some governments are mandating a certain percentage of renewable by certain dates regardless of costs.

This is placing additional stress on existing transmission and distribution systems. The use and development of different technologies is being reviewed to determine how best to fill this need. This project is an example of that trend.

The advent of +/- 800 kV DC has allowed for bulk transmission of very large amounts of power in the 6 000 MW to 8 000 MW range. The first Ultra High Voltage DC Link (UHVDC) was placed in-service at the end of 2009 in China. China has another +/- 800 kV DC link on order and India has also ordered an 800 kV link. China is planning some 100 000 MW of HVDC in the next 15 to 20 years. This information came from ABB at a HVDC Users' Conference in Yechang, China in October, 2007. India is also planning about 50 000 MW in the same time frame. This information presented by Crompton Greaves - India in a meeting Manitoba Hydro in 2007 where Crompton Greaves - India were discussing the possibility of producing HVDC Systems and wanted some feedback from Manitoba Hydro as they also own the Pauwels Transformer factory in Winnipeg Canada. This increasing demand from very large schemes has already placed a strain and is likely to continue placing a strain on HVDC Suppliers.

Some areas of the USA particularly the North East are looking at underwater and underground cables as transmission right of ways get more difficult or impossible to acquire. While underwater and underground cable transmission is generally more expensive in overhead transmission, it may be the only way to get the required approvals for new transmission. Underwater and underground cable transmission over 50 to 60 km generally requires the use of HVDC technology to be feasible.

6.2. Limited number of suppliers

There are only three viable suppliers for current source converters at present, ABB, Siemens and AREVA. They have a two to three year backlog of orders.

The main bottleneck is the “special” converter transformers as there are only a few plants in the world that can supply them. One new HVDC Scheme can require anywhere from 14 to 26 converter transformers. With approximately 3 weeks testing each and approximately 9 months to manufacture, one can see that the supply is very limited. All three suppliers realize this and are planning expansions of existing facilities or retrofitting other existing facilities. ABB is converting the plant in Varennes, Quebec Canada to manufacture converter transformers. Siemens is planning to double the existing plant size in Nuremberg, Germany and AREVA is looking towards Brazil for a second plant. Other possible players may be the Crompton Greaves -Pauwels Plant in Winnipeg Manitoba Canada and possibly TBEA from China.

The same three suppliers are also actively pursuing Voltage Source Converters. VSCs have the advantage in that they do not require the “special” Converter Transformer and could be built in many plants. VSCs are a relatively new technology and are ideal for the connection of renewable resources as they produce both active and reactive power. However only relatively low powers have been constructed to date and the power industry is fairly conservative. VSCs are generally considered “unproven” to date especially at higher power levels. However they are definitely the way of the future and power levels are increasing rapidly. A turnkey advantage is the theoretical ability to have unlimited multi-terminal connections, whereas the conventional LCC is limited to 3 or 4 terminals. To this end CIGRE Working Group B4-52 and IEC 60183 are producing a Standard for HVDC of bus voltages to allow these multi-terminal connections. The same three suppliers will become increasingly busy with VSC orders placing additional demands on them.

It is also not surprising that the suppliers are experiencing a corresponding shortage of human resources knowledgeable in HVDC. Suppliers of all related industries have been hiring away experienced staff from other suppliers, utilities and wherever possible. New utilities do not have a HVDC experience and thus hire the supplier to operate and maintain the equipment for a few years; until they can get their staff trained. Suppliers will then attract staff with experience from utilities and other companies as well. The problem is that the amount of experienced staff is limited and it is really staff just moving from lower pay to higher paying jobs.

The net result is delays in deliveries, long lead times and an increased risk of errors.

These three suppliers also produce AC FACTs devices plus much of the AC Transmission equipment so as demand increases they are under even more stress and pressure.
Also the number of suppliers (ABB, Prysmain, Nexans, Silec) of DC underground cables is also limited and their order books are full for many months. Thus the cable may have to ordered early or the in-service date delayed for the project.

6.3 Finance

The banking crisis has delayed some projects and refurbishments as credit and loans have dried up especially in the developing world. The world demand on electricity growth has slowed which is likely to mitigate some of the issues outlined above.

6.4 Sub-supplier and Raw material Issues

There are also a limited number of sub-suppliers which has resulted in longer deliveries and increases in costs. These sub-suppliers also service the AC Transmission market which is also under the same pressures but usually has more alternatives. For the converter transformers the “special” DC barriers for the DC bushings normally come from Weidman which has increased deliveries times substantially and increased prices; so the major manufacturers of the converter transformers are looking at alternatives.

A few years ago core steel for transformers was in short supply and the cost increased. This situation got so bad that the core steel suppliers would quote you a delivery schedule but a firm price would be quoted prior to delivery. This appears to have resolved itself with transformer steel now more readily available . Copper prices went up 400% also resulting in late deliveries, the price has come down a bit but it is still remains very volatile.

A year ago there was a shortage of silicon wafers to make solid state devices such as computer chips, Thyristors, IGBTs and the price of wafers increased greatly. There is now a resumption of supply and the price has retreated somewhat, but it shows how seemingly unrelated events can significantly impact on the supply chain and costs.

The volatility of commodity prices for copper, steel, and other raw materials, makes it more difficult to do comparisons between HVDC and AC transmission and it is likely most published information on this topic is out dated. While it would appear that raw material prices would affect both HVDC Transmission and AC Transmission equally, different quantities of various materials are required for each.

6.5 Limited UK capabilities in the Supply, Installation and Maintenance

There is general limited capability with a lack of knowledge, good information and experience in applying HVDC Transmission in the UK. Part of the problem is that the technology is advancing so rapidly it is hard to keep up even if you work in the HVDC industry. The other part is that staff may be very knowledgeable and experienced in the AC industry and HVDC is a new and relatively unknown area to them. There is a real lack of good complete information on HVDC Transmission and how to apply it properly. Thus planners and consultants are hesitant to recommend something that is outside their area of expertise.

AREVA one of the main HVDC Suppliers and is based in Stafford UK, is busy with projects in other countries. They also started later that ABB and Siemens in the development of their Voltage Source Converter technology and are only in the development of a prototype stage. Consequentially they have not likely been as active in the UK with marketing and educating their product. The suppliers themselves are usually the main source of information on new technology developments and provide on-going education. The same likely also applies to ABB and Siemens.

HVDC Technologies are more complex than most AC System Technologies and there is a shortage of skilled and experienced personnel in the UK to install commission and maintain this equipment. Even the suppliers are experiencing this shortage. As an example for the Moyle Interconnector between Northern Ireland and the Scotland; Siemens hired engineers from Manitoba Hydro International in Canada to assist in the installation, commissioning and maintenance.

7 Solutions and Barrier Mitigation

With the supply chain issues from the suppliers; there is not much that can be done in the short term and all the suppliers are looking to expand their capabilities although the costs are significant.

With respect to the human resources, one solution would be to introduce HVDC Transmission at the undergraduate level in the university. This would provide a supply of graduates with a basic understanding of HVDC and prepare them for a possible career in HVDC. HVDC uses power electronics as the building blocks so a course in that would help and may already be available. This could be integrated with FACTS and Power Electronics to give a broad range of skills to graduates. With expansion of the electrical engineering curriculum, student content hours in the power engineering discipline has significantly reduced, and this new material could only be delivered by removing other elements of power engineering.

The UK university sector has been for some time active in power electronics technologies for many years and there is a steady stream of academic papers. However investments into this industry are required to further develop the students into practical power system engineers.

Advancing one VSC project of a sizable MW rating would provide much needed practical experience in all aspects of the project. It would also allow any problems which crop up that were unforeseen to be resolved before future VSC schemes are required.

An application guide and reference book should be written to allow easy access “good” information in the public domain for the various HVDC Transmission technologies and it should be updated as necessary. It could include FACTS device and other AC technologies as well remembering that the STATCOM is really part of the VSC family. Such a text book would be the equivalent to the Westinghouse Transmission and Distribution reference book for AC systems

Conferences and seminars on HVDC Transmission technologies would bring an awareness of the various changes and advantages of HVDC. However they are unlikely to give one the comfort level, knowledge and experience to specify HVDC Transmission where the advantages over AC transmission exist. It is likely necessary to have a people knowledgeable in HVDC assist in the transmission review process and projects until staff become comfortable with these technologies.

Voltage Source Converters are a promising new technology. However VSCs are still in their infancy and not proven at higher power levels. They appear to have significant advantages in integrating renewable resources into the grid.

The potential benefits of VSC's make this technology worth pursuing further. Areas to concentrate on are:

- Multi-terminal development
- Low cost XLPE cable development
- Reduced converter losses

A more detailed assessment of each of the areas is required before it can be determined which investments will be most beneficial in speeding up the technology and where the maximum benefits can be derived from that area. Financial resources are limited and the best and highest probability of return on investment would likely be chosen.

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