Appendix Q

Evaluation of HVDC Light® as an Alternative for the Vancouver Island Transmission Reinforcement (VITR) Project

Evaluation of HVDC Light^{TM} as an Alternative for the Vancouver Island Transmission Reinforcement (VITR) Project

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TRANSGRID SOLUTIONS

April 6, 2005

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Dear Mr. Barrett,

Attached please find the final report "**Evaluation of HVDC Light™ as an Alternative for the Vancouver Island Transmission Reinforcement (VITR) Project".** I trust that the information and the findings presented in the report will be helpful for the continued development of the project.

Kind regards!

Yours sincerely

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Introduction

In reference (1) BCTC concluded that a 230 kV AC upgrade is the technically and economically superior option for the Vancouver Island Transmission Reinforcement (VITR) Project. It was also shown to have lower risk and uncertainty compared to the replacement of poles 1 and 2 converter stations of the existing HVDC system. The technical and economic comparison was performed between the following two alternatives:

1. The replacement of the aging existing 138 kV cables installed in 1956 and 1958 between Arnott and VIT with two 230 kV circuits each capable of 600 MW in two stages. Stage 1 is in 2008-2010 and stage 2 in 2018-2019 or when required.

2. The replacement of the existing poles 1 and 2 converter stations of the existing HVDC system with new +/- 300 kV poles rated for 540 MW at 900 Amperes per pole also in two stages. In this alternative, it was assumed that the existing HVDC submarine cables would be reused after performing some repairs.

The studies and comparisons to date did not include a similar comparison between the 230 kV option and the Voltage Source Converter (VSC) technology and, in particular, the technology of HVDC Light^{TM} offered by one manufacturer. Although this report provides a comparison between the 230 KV option and HVDC Light^{TM}, it should be noted that similar VSC technologies are available from other manufacturers under different trade names, such as HVDC PLUS from Siemens. Knowing the current state of the art of VSC, the comparison is also valid for such technologies.

The objective of this report is to analyze and compare HVDC Light^{TM} to the 230 kV ac option based on:

- State of the art of the HVDC Light^{TM} technology
- Technical advantages and disadvantages of both alternatives
- Transmission losses
- Construction costs
- Overload capability
- Operation and maintenance
- Reliability
- Environmental impact

HVDC Light^{TM} Technology

HVDC Light^{TM} (2 and 3) is a trade name of ABB for the Voltage Source Converter (VSC) technology applied to long distance power transmission, back-to-back or Static Var Controllers (SVCs). It was developed for power transmission purposes in 1997 and demonstrated that year in the Hellsjőn project. That first transmission circuit was rated at 3 MW and +/- 10 kV. The design utilized Insulated Gate Bipolar Transistors (IGBT) valves in a three-phase bridge configuration together with high voltage dc capacitor. The IGBT valves have the capability of being controlled in both the turn-on and turn-off directions. This is quite different from the conventional thyristor valves which are used in Line Commutated (LC) HVDC where the turn-on of the valves is controlled but the turn-off is through the commutation process.

The IGBT was developed in 1982 for lower voltages (600-1200 Volts). Voltage Source Converters (VSC) were applied in traction and motor drive applications for years. In the beginning of the 1990s, it was realized that the concept was also feasible for power transmission. This was achievable due to the development of higher voltage IGBTs (2.5 kV, then 3.3 kV in 1997 and 6.5 kV in 2002).

The earlier commercial systems were rated up to 60 MW per bipolar block and used a two level converter topology. Pulse Width Modulation (PWM) techniques are used for the switching of the IGBT valves. In those earlier systems a higher switching frequency was used. The dc voltage was +/- 80 kV. The second generation is the three level converter where the dc voltage is +/- 150 kV and the dc power per bipolar block is up to 330 MW. This latest design has been used in Cross Sound Cable project (330 MW) and the Murraylink project (220 MW). The switching frequency for Cross Sound is 1260 Hz (21st harmonic) and for Murraylink is 1350 Hz (27th harmonic).

In recent technical presentations regarding HVDC Light, ^{TM} ABB has stated that a new generation of IGBTs will soon be available with a converter capacity of 500 MW. However the experience to date has been only with a maximum transmission capacity of 330 MW. This is important because, unless a new generation of IGBTs is developed or the switching frequency can change, similar levels of the power losses can be expected.

Characteristics of HVDC Light^{TM}

A key feature of HVDC, whether it is Line Commutated HVDC or VSC technology, is the fast and precise control of the dc power. HVDC Light^{TM} has the following salient features compared to conventional Line Commutated HVDC:

- HVDC Light™ has the capability of independent reactive power control at each terminal. However, the amount of available reactive power control will depend on the amount of active power being transmitted. It all has to be within the total MVA rating of the equipment.

- HVDC Light™ has higher transmission losses than Line Commutated HVDC. A two level converter operating at a switching frequency of 1950 Hz has power loss of 3% for the complete sub-station. This figure improves to 1.8% per terminal station for the three level converter operating at a switching frequency of 1260 Hz (5) excluding the transmission cables or lines. On the other hand, Line Commutated HVDC has a typical power loss of 0.8% per terminal station excluding transmission lines or cables.

- There is no appreciable difference in the performance of HVDC Light™ and Line Commutated HVDC with respect to frequency control of the ac system.

- HVDC Light™ has an advantage in the case of connection to a very weak ac system. The lowest short circuit ratio where HVDC Light™ has been applied to date is 1.3. Conventional HVDC has been applied in two situations where the effective short circuit ratio is as low as 1.5. Typically if an ac system has an effective short circuit ration below 2.5 it is considered a weak system.

- HVDC Light™ has no overload capability, while line commutated HVDC systems typically provide an overload capacity of 10%

- HVDC Light™ can operate in a passive load or a dead grid. This has been demonstrated in the case of Cross Sound Cable Project.

- HVDC Light™ does not control fault currents for faults occurring on the dc side. The ac breakers must be opened. It is a fact that faults on overhead lines are more frequent and probable than faults on cables. Therefore, HVDC Light™ is used in conjunction with submarine and underground cables not with overhead dc lines to reduce the probability of such faults. The converter is usually designed to handle the fault current until the ac breakers are opened which is typically in the range of 3 cycles. Line Commutated HVDC can be used with both overhead lines or cables. The Line Commutated HVDC applies de-ionization attempts to clear the fault. In most cases the fault is cleared by the first or the second de-ionization attempt and the transmission is resumed. In some situations the transmission can be also resumed at a reduced dc voltage. in the case of HVDC Light™ the ac breakers must be opened making restarts within a short period of time impractical.

- HVDC Light™ can use cables with solid extruded insulation, because the change of power direction is achieved through the reversal of the direction of the dc current not through the reversal of the dc voltage. Conventional LC HVDC must use either fluid-filled or mass impregnated cables, because the change of power direction is achieved through the reversal of the dc voltage polarity. Solid extruded cables as currently manufactured cannot withstand this polarity reversal.

Review of the Present and Future Load/Generation Requirements on Vancouver Island

The information in this section is based on discussions with BCTC and the review of (1). The load on Vancouver Island is currently served by:

- Two 525 kV fluid-filled ac circuits, each consisting of two segments 29/9 km in length. Each circuit is rated 1200 MW for a total of 2400 MW. These cables were put in service in 1983-1984. The cables are in excellent condition, as verified through regular inspections at 3-year intervals. These circuits provide a strong synchronous tie to the mainland BCTC system.

- Two HVDC cables which connect to the HVDC converter stations at Arnott and VIT as follows:

  1) The pole 1 cable, referred to as DC 1, is a mass impregnated cable in two sections 28/4.5 km and is rated for 260 kV. This cable consists of three cables; each is rated for 600 Amps. The nominal rating of the pole 1 Mercury Arc converters which are connected at each end of DC 1 is 312 MW. This means the dc current is limited to 1200 Amps. The cables were put in service in 1969. The cables are in relatively good condition.

  2) The pole 2 cable, referred to as DC 2, is fluid-filled in two sections 28/4.5 km and is rated for 280 kV. This cable consists of two cables; each is rated for 850 Amps. The nominal rating of the pole 2 air cooled thyristor valve converters is 378 MW with an over load capability up to 476 MW dependent on ambient temperature. During overload conditions on the pole 2 the capability of the converters and the cables are matched. The pole 2 cables were installed in 1975. This cable has been repaired in the recent past.

Both pole 1 and 2 cables connect to overhead dc lines.

- Two 138 kV ac circuits. These circuits are currently used to serve load on the Southern Gulf Islands and connected to Vancouver Island only in emergency situations.

- Local generation on Vancouver Island is 689 MW or about one-third of peak load requirements.

Based on the current local island generation and transmission interconnections to the mainland, there is no capacity deficiency to supply the load. However, from a planning point of view, the HVDC system is 30 to 36 years old and cannot be considered dependable indefinitely. BCTC considers that the end of life for the HVDC system is in the year 2007. Although the HVDC system would continue to operate as emergency backup after 2007, it cannot be depended on for firm supply to the island. Based on the load forecast for Vancouver Island, the peak load will exceed the supply by 300 MW in the winter of 2007-8.

BCTC has concluded that Vancouver Island needs to be supplied with an additional 600 MW around the year 2008. BCTC has also determined that an additional 600 MW may be needed by the year 2018.

BCTC concluded in (1) that a single 600 MW, 230 kV ac circuit placed in the right of way of the old 138 kV cables is the most economic and technically acceptable solution when compared to a Line Commutated HVDC solution.

HVDC Light™ Case Study

This analysis of the potential application of HVDC Light™ as an alternate for the Vancouver Island Transmission Reinforcement Project is based on the 2008 requirements of an additional 600 MW. The additional 600 MW in the year 2018 to 2020 is too far in the future to consider here. From a technology point of view, it would be unrealistic and impractical to compare any such future solutions. Technological advances in VSC, power electronics, or cable technology will have to be reconsidered at that time.

Based on the present state of the art in HVDC Light™ (2 and 3), to transmit 600 MW to Vancouver Island, two bipolar blocks each rated for 300 MW are required. Each bipole will require two submarine dc cables of approximately 33km in length as well as two underground cables on the land portions of the route to connect to the converter stations. The dc voltage will be in the range of +/- 150 kV with a current of 1000 Amperes.

HVDC Light^{TM} Characteristics for Vancouver Island Transmission

A 600 MW HVDC Light^{TM} transmission link between the mainland and Vancouver Island can provide accurate control of power flow on the circuit. However, this feature is not unique to HVDC Light^{TM} as this can also be provided by conventional Line Commutated HVDC. The unique feature of HVDC Light^{TM} is that, in addition to the control of the active power, it can also control the reactive power independently at each terminal. In principle the VSC can be considered as equivalent to a synchronous generator without inertia. In this case each bipolar block can be expected to be able to control the reactive power in the range of +/-75 MVARs. Although this is a potentially good feature, it should not be considered on its own. The reactive power supply on Vancouver Island and its control is not currently a problem for the following reasons:

- There are 4 existing synchronous condensers providing dynamic var support from -250 to +300 MVARs.

- Once the existing HVDC system is decommissioned, the existing ac filters (capacitors) at VIT can provide switched capacitor reactive power support in the range of 170 MVARs.

It should be also kept in mind that if the aim is to transmit 600 MW then the reactive power control range is severely limited by the total MVA rating of the dc circuit.

It is true that HVDC Light^{TM} can operate in very weak ac systems or remote isolated loads where there is no local generation as in the case of offshore systems such as oil production platforms. However, in the case of Vancouver Island, the system has a strong synchronous connection to the mainland with two 500 kV ac cables. There is also local generation on the island of 689 MW. In this regard, HVDC Light^{TM} would provide little advantage. The Vancouver Island ac system can hardly be referred to as an isolated weak ac system.

System Losses

The losses in VSC's consist of both no-load losses and load losses. The no-load losses are those that arise continuously, even when transmitting no power or reactive power exchange with the ac system. These losses occur in the interface transformers, filters, phase reactors and auxiliaries. The load losses occur only when power is transmitted or during reactive power exchange. In order to understand why HVDC Light^{TM} has higher loses than Line Commutated HVDC we should understand its principles of operation.

HVDC Light™ uses IGBT valves. The IGBT valve can be controlled on turn-on and turn-off. The IGBT control is accomplished by using a pattern of MOS transistors distributed on the surface of the device. To obtain the rated current capability, the IGBT is made of a number of chips connected in parallel. An anti-parallel free wheeling diode is used to ensure the reverse current capability and to prevent the application of reverse voltage.

The losses in the IGBT (6) consist of three main components, the on-state or the conduction losses, the turn-on losses, and the turn-off losses. The on-state losses depend on the average and rms current in the IGBT, as well as on the power factor. Losses are caused by the IGBT fixed forward voltage drop and the IGBT conduction resistance. The other two components, turn-on and turn-off losses, depend on the current and voltage at each switching occasion, the switching frequency, and the characteristic of the device at turn–on and turn-off. The losses in the diode part are determined in the same way; the diode has negligible turn-on losses, since it turns on as soon as forward voltage appears. The turn-off loss due to diode recovery is not negligible.

The inverter operation is thermally decisive for the IGBT part, and the rectifier operation is thermally decisive for the diode part. High power dissipation for IGBT turn-on and turn-off is due to the fact that the device is subjected to high current and high voltage simultaneously during a good part of the switching process. To reduce these losses the device should switch as fast as possible, that is, at voltage and current derivatives as high as possible.

A three level IGBT-based VSC with a switching frequency of 1260 Hz has a power loss of 1.8% per terminal (5). This means that, for the 2x300 MW HVDC Light™ transmission envisaged for Vancouver Island, the total losses for the terminals without losses in the 4 cables is about 22 MW. If we consider a resistance per cable of 2 Ohms, the total losses in the 4 cables would be 8 MW. This means that the total transmission system losses are 30 MW. This figure is not far from the transmission losses measured in the Cross Sound Cable, which is rated at 330 MW. The measured transmission losses were 14 MW (2), which is 4.2%. If we consider the 2x300 MW in this case the losses would be 28 MW.

The estimated transmission losses for the 230 kV ac option are 17 MW (8).

Reliability

It is difficult to evaluate the actual reliability of HVDC Light™ simply because there are few systems in commercial operation, and the ones that are in service have been in service for only two years. This does not mean that VSC is unreliable, but it is relatively unproven compared to ac systems or to conventional Line Commutated HVDC where experience spans almost 50 years. The reliability of any HVDC system is a function of the reliability of its sub systems such as valves, high voltage equipment, transformers, control and protection, and auxiliary systems. There is no reason to think that these components in HVDC Light^{TM} will be any less reliable than Line Commutated HVDC. The only difference is that there has not been long experience with IGBT valves.

The reliability of the components and the sub systems can be considered a steady state type of function, it is a static reliability related to the potential failure of components and the level of installed redundancy. Reliability is also affected by the behavior of the system during faults and disturbances, which could be referred to as dynamic reliability. There are two fault conditions where VSC behaves different from Line Commutated HVDC

- HVDC Light^{TM} cannot mitigate, by control action, large system overvoltages due to the action of the free wheeling diodes. The converter has to be tripped and blocked.

- HVDC Light^{TM} cannot control the current for dc side faults due to the action of the free wheeling diodes. The converter has to be tripped via its ac circuit breaker. Therefore if it is used with an overhead line, the typical deionization attempts used in Line Commutated HVDC can not be applied. DC line faults on overhead lines are very common. In the case of HVDC Light^{TM}, it has only been used with submarine or underground cables and not with overhead dc lines.

Cables

For HVDC Light^{TM} consisting of 2x300 MW bipolar blocks at +/- 150 kV, four cables are required. For VITR, each cable would include both submarine and underground sections. Each of the four cables will carry 1000 Amperes. Solid extruded insulation cables cannot withstand polarity reversal. However, HVDC Light^{TM} can use them since it changes power flow direction by reversing the dc current.

The cross section of the dc cables will be typically 1000-1200 mm^2 if laid attached or 600-800 mm^2 if laid separate. The cables can be laid attached in shallow water. If we compare this with the single circuit 3 phase 230 kV cable for 600 MW, the current is 1500 Amperes per phase. Three cables 1600-2000 mm^2 are needed. These cables are laid separately and the cables would be shielded to reduce the induced current losses.

From a cost point of view, the ac cables are more expensive per unit length; but the overhead sections are much less expensive. For HVDC Light^{TM}, the entire route would have to be submarine/underground cables.

The installation costs are also very important and, in particular, the degree of protection required (burial). This tends to reduce the difference especially in the case of HVDC Light^{TM} where we have to deal with 4 cables. In the cost analysis of HVDC Light^{TM} the cables have been assumed to in bundles of two and laid attached. An alternative for the ac cables is to provide two 3 core cables (3x600-800 mm^2). This means the cores are incorporated in one common armor each for 300 MW. The installation cost here is much lower than the four dc cables and than the larger ac cables as there are only two burials. It is similar to the bundled dc cables.

Environmental Impacts

HVDC Light^{TM} is very similar to conventional HVDC using Line Commutation from an environmental standpoint. The same issues have to be dealt with:

- Visual impacts
- Audible noise
- Electric and magnetic fields
- Electro magnetic compatibility

All these have to be dealt with similar to Line Commutated HVDC.

Economic Evaluation

In any project, evaluating the technical advantages and disadvantages of the possible alternatives is only one aspect of project development. The economics and the life cycle costing of the different alternatives are also very important.

The life cycle costing of HVDC Light^{TM} is influenced by:

- Procurement and installation costs.
- Interest and inflation rates
- Cost of spare parts
- Cost of system losses

- Cost of annual or periodic maintenance.
- Useful operating life of the facilities and equipment

The same principles are applicable for the 230 kV ac alternative.

Line Commutated HVDC is a mature technology and the price per kW of installed converter stations is readily available based on evidence of awarded projects worldwide. Although prices are always project specific, a reasonably accurate indication of the price can be established by looking at several real projects. On the other hand, HVDC Light™ has been around for a very short time, and there are few projects to draw such conclusions from. It is safe to say that for HVDC Light™ the price per kW is either the same or even higher than conventional HVDC (9). In Appendix 1, a complete estimated cost breakdown of the HVDC Light™ option is given. The cost of HVDC Light™ for 2x300 MW bipolar blocks is Canadian 306 M$ (Appendix 1). On the other hand, the cost of the 230 kV ac option for 600 MW in 2003 (1) is Canadian 168 M$.

The following gives an economic comparison between the 230 kV ac option and HVDC Light™:, cost comparisons do not include allowances for escalation or contingency.

Table 1

	HVDC Light™ 600 MW	**230kV AC Cables 600MW**
Capital Cost	306 M$ CAD	168 M$ CAD
Transmission Losses	30 MW	17MW
Spare Parts Requirements	High spares requirements since it includes spares for practically all the station equipment and for both terminals.	Low
Operation & Periodic Maintenance	More equipment to maintain. It is estimated at 1.33 M$ CAD/year which is 0.5% of the capital cost of the installation.	Low. There is only one set of cables and the phase shifter.

Conclusion

An HVDC Light™ option for VITR rated 600 MW has been compared to one 3 phase 230 kV ac circuit rated the same. The two systems were compared from the standpoint of:

- Technical performance
- Energy losses
- Reliability
- Costs

- Environmental impacts

For VITR, HVDC Light™ is more expensive to construct, has higher losses, and costs more to maintain than the 230 kV ac alternative. It does not offer any technical advantage in this situation simply because:

- Vancouver Island is not a weak ac system, where the HVDC is the only in feed.
- The reactive power support and its control on the island is not a problem.
- There already exists a strong ac connection between Vancouver Island and the mainland via the two 500 kV ac cables.

Appendix 1

- The price per KW for HVDC with Line Commutated (LC) installed is Canadian 236 $ /kW
- The price per kW for HVDC Light™ sub stations installed is Canadian 283 $ /KW. This figure is taking into consideration that it can be higher than the price of Line Commutated (LC) HVDC by 20%.
- The price of the HVDC Light™ converter stations installed is Canadian 170 M$
- For the dc cables and considering that the four submarine cables are in two cables attached together which means two runs and two burials, cost is Canadian 42 M$. This is based on a price of Canadian 700,000 $ per km, and a cable length of 30 km for the submarine cables. Assuming the existing sites of Arnott and VIT are used for the new HVDC Light™ converter stations, then there is an additional 40 km of new land cable or the use of the existing overhead lines. If the existing overhead lines are used instead of cables, this will impact the overall reliability of the system. If we assume the same price per km the cost of the land cables is estimated to be Canadian 56 M$. The total cost of the cables is Canadian 96 M$.

The cost of the project installed as a turn key including civil works , terminal stations, and cables is Canadian 266 M$. If the engineering costs of BCTC to realize the project of Canadian 40 M$ are taken into account. The total cost of the project would be 306 M$. The assumption here is that the new equipment is installed at the existing sites. This means no major improvements are needed to the sites or site preparation. If new sites are envisaged then obviously additional costs for site preparation as well as additional environmental licensing is required. The site preparation costs will depend on the location and conditions.

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