DCI

REPORT

Feasibility of Using HVDC Technology

For

Reinforcing the Interior to Lower Mainland Transmission Grid

BCTC Reference No.: 300209

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EXECUTIVE SUMMARY

At the request of the British Columbia Transmission Company (BCTC), DC Interconnect, Inc. (DCI) has conducted an assessment of the potential competitiveness of high-voltage dc (HVDC) technology with a benchmark extra-high voltage ac (EHV AC) investment the 5L83 transmission project. It is assumed that the 5L83 EHV AC benchmark would be energized in 2014 for the purpose of increasing the thermal power transfer capacity of the Interior-to-Lower Mainland (ILM) transmission interface to provide 2100 MW of additional thermal overload capability by 2026.

An additional task to assess the competitiveness of HVDC against a benchmark EHV AC with lesser reactive requirements and henceforth lower transfer capability was added upon completion of the original assignment. Based on new BCTC analysis of the reactive support needed to increase the ILM transfer, an HVDC option with less thermal transfer capability and an achievable reactive requirement is also presented.

DCI analyses for the 2100 MW incremental expansion of the thermal overload capability of the system indicate:

1. It is technically feasible to meet a future ILM 2100 MW incremental thermal overload N-1 transmission capacity expansion (to a total of 8400 MW) by using conventional HVDC technology in the form of a new 500 kV 2200 MW dc line in place of the 5L83 benchmark (i.e., within the right of way (ROW) designed for 5L83);
2. Constructing a 500 kV conventional ac circuit without series capacitors followed later by conversion to bipole dc also represents another approach involving the application of conventional HVDC technology that can be considered technically feasible for meeting the specified ILM expansion requirements;
3. In spite of being technically feasible, conventional HVDC transmission does not appear to be economically competitive with 5L83 as currently contemplated by BCTC;
4. Assessing the economic impacts of loss differences between the ac and the dc versions of 5L83 will not alter the cost gap between the ac and dc alternatives;
5. Converting existing ac circuits 5L81 and 5L82 into HVDC will not meet the ILM reinforcement requirements as stated by BCTC; and
6. Tripole HVDC transmission offers certain conversion advantages but remains an untried technology.

DCI analyses for the reactive-limited ILM transmission expansion and lesser power transfer capability indicate:

1. An HVDC expansion of the ILM to a total continuous N-1 thermal capability of 6750 MW (or 1750 MW of incremental increase) and a voltage stability limit of 7120 MW (or 1320 MW of incremental increase) with a 470 MVAr reactive limit can be achieved by a new 500 kV bipole HVDC circuit with a continuous thermal capability of 2000 MW.
2. Although the 500 kV bipole HVDC circuit exceeds the technical capabilities identified by BCTC and requires somewhat less than the 470 MVAr BCTC specified reactive support, it is not economically competitive with the 500 kV 5L83 EHV AC 470 MVAr reactive support limited option.
3. Converting existing ac circuits 5L81 and 5L82 to HVDC bipole will not meet thermal requirements with a reactive limited expansion plan. Conversion to tripole appears to be technically feasible.

ROW and substation space requirements are outlined. However, determining their availability and acquisition costs was not within the scope of this study.

All costs provided in this report are planning level estimates in keeping with the BCTC HVDC Analysis 300209 Terms of Reference.

Disclosure

This is to give notice that Mr. Lionel O. Barthold (LOB) who is subcontracted to DC Interconnect, Inc. (DCI) to assist DCI in the provision of services contracted to the British Columbia Transmission Corporation (BCTC) under BCTC's letter of March 2, 2007, holds a patent on certain technology referred to in this DCI Report. Specifically, LOB holds US Patent 6,714,427 B1, March 30, 2004 "Current Modulation of Direct Current Transmission Lines" (the Patent). The technology contained in the Patent is referred to in this DCI Report as tripole.

Disclaimer

DCI has prepared this Report for the sole use of BCTC and for the intended purpose as stated in the BCTC letter dated March 2, 2007 under which this Report was completed. The Report may not be relied upon by any other party without the express written agreement of both BCTC and DCI. DCI understands and expressly agrees that this report may be relied on and submitted to the British Columbia Utilities Commission as part of an application by BCTC to enhance or upgrade the capacity of the ILM grid.

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Glossary

Short Circuit Capability

When a short-circuit occurs on a bus or transmission line high "fault" currents flow from generators to the location of the fault. A high fault current indicates a strong system wherein change in load will cause little change in the voltage. Such a system would be considered to have an adequate short circuit capability.

Commutation

A conventional HVDC converter is said to be "line commutated." The commutation process involves shifting the current flow from one thyristor to the next. That transition imposes an extremely brief but large current on the ac system. If the ac system voltage changes excessively as a result of that current, the commutation may fail to occur and the HVDC converter will be shut down. Where short circuit capability is sufficient to allow little change in voltage during commutation, HVDC converter operation will be reliable.

Ground Electrode

Use of earth return current requires a ground electrode. A ground electrode must allow several thousands of amperes to be conducted into the earth with little drop in voltage. Once that current is in the earth, it spreads out and finds many paths to the other end of the HVDC line. Collectively, those many paths of low-density current provide a low resistance to power flow. However, at the current density in the vicinity of the ground electrodes is high and even a small resistance can be troublesome. If the ground is not moist and highly conductive, chemicals and moisture can be added to provide the needed low resistance.

Thermal Overload Capability

Thermal overload capability is that power that a transmission system can transfer immediately following a contingency (e.g. a line outage) without risking equipment damage. During this period some lines and transformers will generally be operating above their continuous capability and below their shot-time overload capability. Operators will first attempt to restore the outaged equipment to service. If it appears that this will not happen in a timely fashion, they will shift their efforts to system adjustments to relieve the overloads and restore the system to a secure state where it can accommodate yet another contingency.

Continuous N-1 Thermal Capability

limit. The power transfer limit imposed on a transmission grid by the continuous thermal ratings of equipment during the outage of any one of those pieces of equipment (commonly referred to as an N-1 condition). It is reached when the most heavily loaded element reaches its continuous thermal rating. The transfer limit can apply until the outaged element is returned to service. Other operating constraints such as reactive power availability and voltage stability may supersede the N-1 thermal capability by imposing lower transfer limits.

Concatenated

This word is used to describe removing two ac circuits from an ac grid, connecting them in series and adding HVDC converters at the ends to make one long HVDC line. While no examples of concatenated lines exist, the concept is gaining greater attention with the increased advancement and application of HVDC technology.

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1. INTRODUCTION

British Columbia Transmission Corporation (BCTC) has evaluated alternative high-voltage alternating current (EHV AC) transmission investments to provide increased transfer capability from Interior generation to load centers in the Lower Mainland and also conducted studies on the cost of reactive power to achieve the increased ILM transfer capability. BCTC has retained the services of DC Interconnect, Inc. (DCI) to conceive and evaluate additional options making use of high-voltage direct current (HVDC) technology. Although, at the time of this study, the evaluation of EHV AC alternatives has not settled on a specific option for achieving the desired expansion across the Interior-to-Lower Mainland (ILM) transmission interface, BCTC has identified a specific 500 kV ac investment as a benchmark (reference) case for assessing candidate HVDC ILM upgrade solutions to the existing ILM shown in Figure 1.

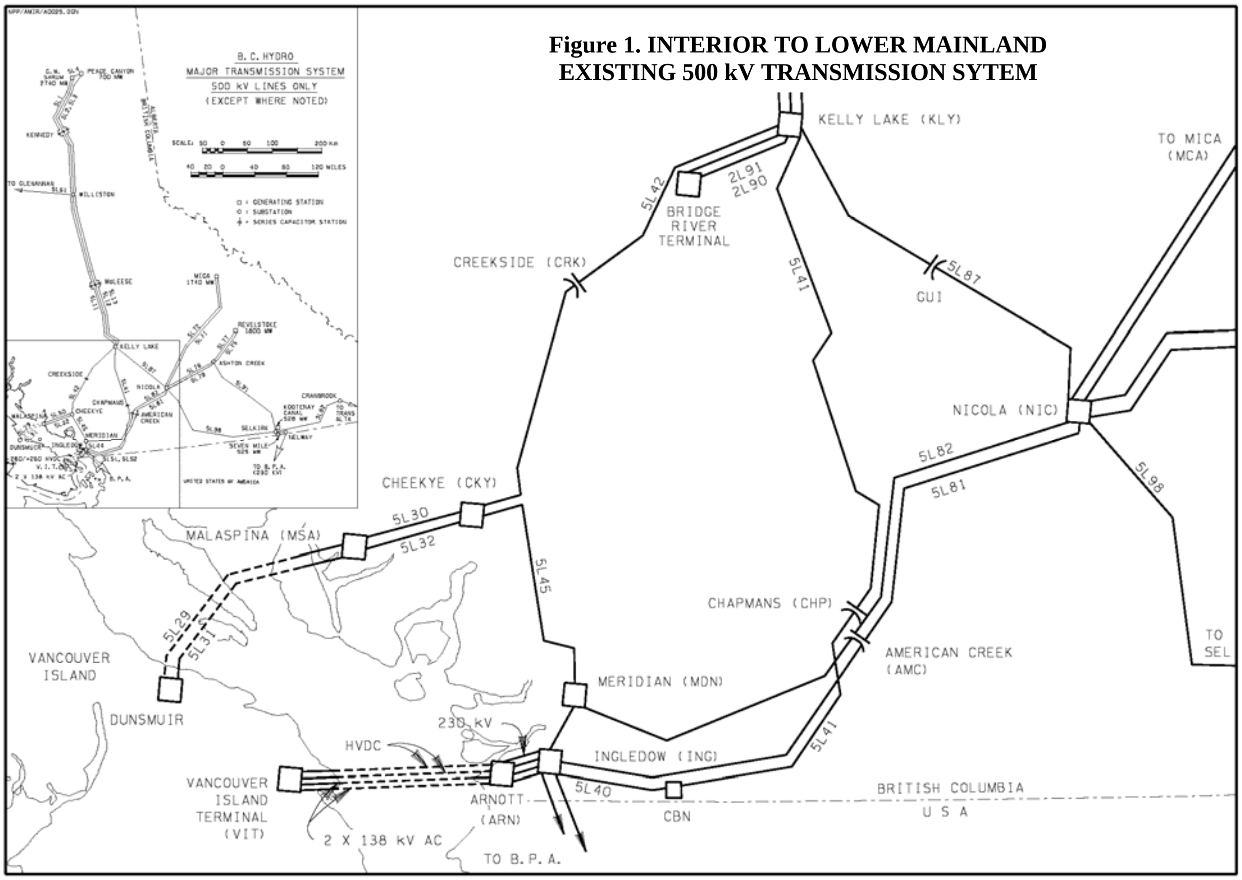

Figure 1. INTERIOR TO LOWER MAINLAND EXISTING 500 kV TRANSMISSION SYTEM

BCTC defines the existing ILM as follows:

The existing ILM transmission network includes the following five 500 kV circuits:

a) 5L41: Between KLY and Clayborn (CBN) substations, series compensated at Chapman Capacitor Station (CHP).

b) 5L42: Between KLY and CKY substations, series compensated at Creekside Capacitor Station (CRK).

c) 5L81: Between NIC and ING substations, series compensated at American Creek Capacitor Station (AMC).

d) 5L82: Between NIC and MDN substations, series compensated at AMC.

e) 5L87: Between KLY and NIC substations, series compensated at Guichon Capacitor Station (GUI).

In addition, three LM 500 kV circuits 5L40 between CBN and ING, 5L44 between MDN and ING, 5L45 connecting CKY and MDN and the 230 kV circuit 2L90[1] between KLY and Bridge River Terminal (BRT) are considered part of the ILM network.

Both transmission paths "Interior to BC-US Border" and "BC-Alberta Border to BC-US Border" include the entire ILM transmission network. Power from generating resources in North Interior (NI), South Interior (SI), and Alberta passes KLY and NIC on its way to BC-US western inter-ties. Shortage of ATC on the ILM grid will restrict the power flow on both paths. Because of the restriction, the ILM will become one of the bottle necks of BC transmission grid for dispatching the Interior and Alberta power.

The benchmark case for this study is a new series-compensated 500-kV ac line named 5L83. Preliminary BCTC studies have established that 5L83 would enable it to provide a 2100 MW increase to 8400 MW in ILM thermal overload transfer capability. Subsequent BCTC analyses indicated that reactive constraints may not allow 5L83 to achieve a 2100 MW of incremental thermal overload capability increase. Adding 5L83 will increase the continuous thermal rating of the ILM grid from the existing 5000 MW to approximately 6750 MW. A reactive compensation availability of 470 MVAr would increase the voltage stability limit of the ILM grid from the existing 5800 MW to 7120 MW.

DCI's assignment was to identify potentially competitive HVDC alternatives to the benchmark case 5L83. Specifically, a dc option would be considered promising if DCI were to find:

- It is capable of providing the incremental ILM transfer capability attainable with the ac 5L83 case;
- It could meet BCTC and WECC planning and operating reliability criteria;
- It exhibits no excessively costly operation and maintenance requirements;
- Its export capability matches what is expected from 5L83;
- It must not lead to intolerable transmission outages during construction; and
- The net present value (NPV) of the total cost of undertaking would render it competitive with 5L83.

The objective of this study is to identify HVDC applications that could be deemed competitive with 5L83 per the above criteria. The approach used to achieve this objective is to: (i) configure practicable HVDC options subject to the above criteria, and (ii) estimate and compare the total cost of the identified alternatives. The economic assessment of HVDC options and 5L83 includes consideration of equipment costs and ILM losses. BCTC **r**equested assessment of equipment space needs but land requirements are not part of this study.

[1] There are two 230 kV circuits 2L90 and 2L91 between KLY and BRT. In July 2002, Circuit 2L91 was damaged in a forest fire and is currently used as a 60 kV circuit.

Sections 2 through 6 are dedicated to the original DCI assignment: the development of HVDC options that compare with 5L83 benchmark capable of sustaining a 2100 MW of incremental thermal overload capability. Section 7 presents the results of additional BCTC-requested analysis to define and assess HVDC options that account for reactive constraints limiting incremental thermal capability gains to 6750 MW continuous N-1 capability and a 7120 MW voltage stability limit.

2. HVDC TECHNOLOGY

Although HVDC transmission is a mature technology, it is currently undergoing promising evolution. For this reason alone, it is worthwhile to take into consideration both conventional dc transmission and new developments that may affect long-term investment decisions. The fact that 5L83 is subject to energization in 2014 and is aimed at expanding the ILM transmission capacity by 2100 MW as of 2026 further reinforces the case for considering future advances in HVDC transmission.

Conventional HVDC Technology

The first HVDC transmission lines were constructed in Russia and Sweden in the 1950s. Those early projects led to higher capacity valves and higher voltages[2]. According to information recently assembled by the IEEE Working Group on HVDC and FACTS Bibliography and Records on world-wide HVDC applications, seven HVDC projects went into service in the 1960s, 15 in the 1970s, 37 in the 1980s, 25 in the 1990s, and 25 since January 1, 2000. There are also 50 HVDC projects currently under construction or planned for completion by the year 2020. The modest drop in the 1990s is part of an overall decline in all transmission construction activities. It is expected that investments in HVDC transmission will continue to grow with increasing demand for access to distant resources. Although most of the planned projects belong to the conventional bipole technology they involve extended voltages and power ratings reaching +/- 800 kV and 6,400 MW.[3] Appendix A provides a brief description of conventional HVDC technology.

BCTC experience with HVDC dates back to 1969 with the installation of a mercury arc monopole 138 kV HVDC system between Arnott and Vancouver Island Terminal. A second thyristor valve of opposite polarity monopole was added in 1976. The first pole is now normally operated in standby and no longer has any dependable capacity. The second valve has been de-rated and it will be rated at zero for planning purposes for the winter of 2007/2008. Appendix B provides additional details.

New Options and Application Prospects

Conventional bipole technology is no longer the only HVDC option available. The recent introduction of Voltage-Sourced Converters (VSCs) is opening new opportunities for HVDC investments. VSCs will soon achieve converter ratings of 1,000 MW or more in back-to-back and dc cable installations. Application of the

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[2] A valve is a series assembly of thyristors with triggering circuits and water cooling mechanism along with associated transient voltage and current damping components of resistors, capacitors and inductors, of which 12 such valves are assembled into an AC to DC converter.

[3] The term bipole refers to the conventional HVDC transmission of energy by way of one 12 pulse converter for the positive polarity and another 12 pulse converter for the negative polarity, both of which are assembled in each converter station at each HVDC line termination.. See Appendix A for more detail.

new technology is limited to back-to-back and cable systems largely because dc fault clearing requires complete converter shutdown and re-start with the converter configurations presently used. When a dc line fault occurs with VSC transmission, it can be cleared only by using: (i) a readily available (back-up) series valve with the same turn-off properties as the VSC converter valve but rated to continuously conduct full load current, or (ii) the ac breakers that connect the VSC converter to the ac system busbar. Adding a series valve doubles converter losses and significantly adds to its cost thus ruling out use of current VSC technology for overhead HVDC line use. Clearing using the ac breakers leads to requiring converter valves to withstand the ability to survive the fault current until the breaker clears – and possibly until back-up clearing is achieved for breaker failure conditions. This also adds significantly to equipment costs. For these reasons, DCI did not include the application of VSC technology as an option for reinforcing the ILM interface.

Another HVDC innovation is the emerging current-modulated dc transmission or "tripole" HVDC. The new technology makes use of conventional HVDC monopoles and bipoles connected in parallel and operating in a manner that averages the thermal loading of the lines to eliminate the need for earth-return current. While not yet in use, tripole transmission could render converting three-phase ac lines to HVDC much more economic than at present since it makes full use of the thermal capability of all three ac phase positions. New HVDC lines designed at the outset for tripole operation are also possible. Because of its potential advantages and the timing of the BCTC's need for additional transfer capabilities, tripole has been included as an HVDC option as described further in this report. Appendices C, D and E provide more technical details on this technology.

Reliability Issues

Conventional HVDC technology is generally viewed to be sufficiently reliable to allow the North America Electric Reliability Council (NERC) and the Western Electricity Coordinating Council (WECC) to treat a bipole circuit as two, nearly independent circuits. In the best case a bipole line is treated like two ac circuits on a common tower. Loss of one pole leaves one pole that can continue operating at about half the capacity of the bipole line. Additionally, the remaining pole, like the remaining ac circuit, may have overload capability. However, there can be limitations in the design of a bipole line that make it less effective than a double-circuit ac line. To be fully comparable to a double-circuit ac line, the bipole line must have a return path that will allow it to operate continuously in monopole mode. This continuous return path can be provided by a metallic return, for instance an insulated shield wire, or by an earth return (ground electrodes). If a metallic return or an earth return cannot be used indefinitely and at full rated monopole power, then operation of the remaining pole will be constrained to a lower power level or to a limited time period or both. In this case a bipole line will not be fully equivalent to a double-circuit ac line.

A bipole HVDC line may also differ from ac circuits in the amount of overload capability it provides. Overload capability can be designed to match that of an ac line, though the cost of doing so must be recognized. The overload comparison may be less important if the comparison is, for instance, between a 2000 MW ac line and a 3000 MW bipole line.

If a fully rated continuously rated return path is available, loss of one pole results in halving of the thermal capability of the HVDC line – as opposed to losing the entire capacity of the circuit. In effect, a 3000 MW HVDC bipole transmission line is treated from a system reliability perspective, as nearly equivalent to two, separate, 1500 MW ac circuits placed on the same towers, and fully equivalent if it provides matching overload capability.

ROW requirements of a bipole HVDC line would be less than that of a double-circuit ac line of the same rating. Comparing a bipole line with two ac lines (each on its own towers) shows a ROW requirement that is just 30 percent of that for the two ac circuits. Generally a bipole line will not equate to two ac lines, though if the greater N-2 impact of the bipole line (tower outage) are tolerable, the two might compete for an upgrade task.

The increased transmission capacity and ROW utilization advantages of tripole technology (relative to EHV AC) are more pronounced than in the case of bipole applications. A tripole configuration loses only 27 percent of its power transmission capability upon the loss of a pole; and even less if overload capability is taken into account.

The more onerous reliability criterion for HVDC systems is often the N-2 requirement in Category C of the WECC criteria. HVDC lines tend to be high capacity lines and a tower outage imposing loss of "two circuits" composing such a high rating may be difficult to accommodate with system adjustments in present-day grid configurations and re-dispatch constraints. Stability issues may also arise from the loss of such a high capacity line.

Earth-Return Requirement

For a bipole HVDC line to operate monopole during outage of one pole, it must have a metallic return conductor or be able to use the earth as a "ground return." A metallic return conductor can be in the form of a conducting shield wire or a third conductor with less insulation than a pole conductor. An insulated shield wire can also be used to substitute for a failed pole, possibly at a reduced voltage and power loading level.

Moving large dc currents through the earth for extended periods can cause cathodic damage to pipelines, electrify fences, be problematic for railroads, and other equipment that tends to provide a conductive path more-or-less parallel to the HVDC line. Careful design of ground electrodes and limited duration of monopole operating times can usually mitigate these potential effects. However, a short-time rated earth-return may have reliability implications in that a second system adjustment will be needed when the failed pole can not be restored before the earth-return time limit has been reached.

Behavior in an ac Grid

HVDC transmission lines behave differently than ac lines. While ac transmission lines exhibit characteristics that obtain from Kirchoff's laws, HVDC circuits respond only to control signals. An HVDC line thus will not inherently provide synchronizing power during a power swing. Consequently, without sufficient capacity of parallel ac circuitry or other stabilizing method, stability constraints could be problematic. The alternative to having adequate paralleling ac transmission capacity or other stabilizing method, is to provide controls that enable an HVDC line to mimic the behavior of ac circuits during power swings. Because HVDC controls can respond very quickly, it is possible for an HVDC line to be more effective in providing needed synchronizing power than an ac circuit. This is demonstrated in Figure A2 of Appendix A where the "HVDC synchronizing power" can rise quickly rather than build up gradually as an angular swing progresses.

HVDC has the potentially important advantages of not increasing the short circuit capacity. However, HVDC converters require sufficient short-circuit capability to ensure ensure successful transfer of current from one HVDC valve to the next, also known as commutation and thus also demand a minimum short-circuit contribution from the ac system. Where the required short-circuit capability is not available or not always available (for example, during ac equipment outages or during system restoration), either line operation would have to be constrained or supplementary voltage control in the form of Static Compensators (STATCOMs) or synchronous condensers would have to be used. Constrained line operation may involve restoring ac equipment before the HVDC line can be put back into service. Voltage control equipment can be costly.

HVDC lines have the advantage of line fault clearing and rapid re-start with less impact on the adjacent ac system than is the case with an ac circuit.

Power Flow Control

The ability to control power flow offers potentially significant advantages. Power flow on HVDC lines can be adjusted automatically through local controls and/or automatically or manually by remote control from operation centers. The control would be much like one might have to switch the amount of series capacitors in an ac line or adjust a phase angle regulator. Unlike such devices however, an HVDC line inherently provides this capability and allows rapid adjustment. This capability may be used to automatically respond to contingencies in the ac system or re-distribute power flows following ac contingencies. It can also be used to direct power flows to minimize system losses under normal operating conditions then switch to an emergency power level upon a contingency.

Unmanned Station Operation

Modern HVDC converter stations tend to be un-manned and remotely operated. Where required, station personnel in general attend during normal work hours with no local attendance required during other hours. Unmanned operation might be implemented only following six months or a year of manned operation to "prove" the line.

Conversion of ac Lines to HVDC

EHV AC lines can be converted to HVDC to:

- Achieve higher thermal ratings;
- Make better use of thermal capability through power flow control; and
- Optimize loss allocation between dc and ac circuits.

A converted ac circuit may use either two conductors, with the third serving as an emergency ground return, or one conductor for one pole and the other two in parallel for the other pole. The latter configuration reduces losses by 25 percent but has certain operating disadvantages such as requiring mechanical switching to achieve bipole operation following loss of one conductor. Allowable dc voltage is a function of the converted ac line parameters, but may be higher than the crest of the ac voltage, thus increasing power transfer capability for a given level of conductor current. EHV AC insulators are unsuitable for dc and should be replaced as part of the conversion effort. This in turn provides an opportunity for optimizing the length of the insulator strings as well as the ground clearance of the conductors in accordance with HVDC industry practices.

In summary, the bipole reutilization of prior transmission investments is either limited to two phase positions or to three. In both cases two of the three positions each provide half the HVDC capability, each forming one "pole" of the bipole line. The third conductor can be placed in parallel with one of the others to reduce losses or can be applied as a metallic return to avoid using earth return during single-pole operation. It may also be switched to replace either pole conductor and return the line to full capability when a pole is forced out of service and cannot be returned to service within the allowable operating time of the ground return or in a timely fashion as dictated by system needs.

The operating and reliability characteristics of dc transmission may have an important bearing on the transfer capability of parallel ac circuits as discussed elsewhere in this report.

Cost Issues

These issues fall under three categories: (i) The interplay between terminal and line costs, and transmission loss savings over long-distance applications; (ii) Operating expenses and inventory carrying costs; and (iii) Life-cycle costs. With respect to the first category, while HVDC is burdened by high terminal costs, it offers significantly lower overhead-line costs relative to its power handling capability. Hence HVDC is most attractive for long-distance applications. The technology also offers lower losses in comparison with EHV AC for sufficiently long transmission distances where reduced HVDC line losses exceed the additional losses at converter stations. Therefore, where losses are costly, the break-even distance is reduced.

Operating and inventory carrying expenses are not as significant as the high, upfront costs of converter terminals. However, such expenses can be an important tie breaker in situations where the HVDC and EHV AC options under consideration involve comparable capital costs after netting out the present value of loss savings that might be available for certain HVDC applications.

The third category of cost issues involves the life-cycle replacement costs of major system components of HVDC facilities. EHV AC lines have demonstrated useful life spans exceeding 50 years. EHV AC terminal equipment (circuit breakers and switches) possess useful life of only 30 to 40 years, but are not costly to replace. HVDC transmission lines should match historical ac lines performance. It is, therefore, the replacement of relatively large amounts of equipment encompassing the HVDC converters (terminals) that give rise to life-cycle cost concerns.

In 1969, the industry made the transition from mercury vapor electric rectifiers to silicon rectifiers with the installation of the Eel River back-to-back dc link in New Brunswick. Early silicon rectifiers have been replaced with modern thyristors such as in the Miles City back-to-back dc link in Montana. Other converters of similar generation that have been in service over 30 years are now under consideration for replacement with modern thyristors or valve modules. This is driven largely by reliability issues where component failure rates have become unacceptable for some early silicon rectifier valve designs. However, not all existing converters are presently candidates for thyristor replacement or valve upgrade.

HVDC converter control software is more problematic than the larger converter hardware elements. Computing equipment becomes obsolete quickly as does the associated control software where the skills of the personnel installing and maintaining that equipment are no longer available and new control hardware and technology has emerged. Digital controls and software thus tend to be updated on a cycle as short as ten years. Often the updating brings new valuable features and higher reliability, but nonetheless, it is a life-cycle consideration. There are pressures on dc equipment suppliers to adopt a “plug and play” approach to controls. This would significantly simplify hardware and software replacement and upgrading process. In any event, control hardware and software updating is not a significant cost or complexity issue in the evaluation of HVDC options.

Cooling systems require attention as converter stations age, with a trend towards dry-type cooling to conserve the de-ionized water used for cooling the converters. Fifteen years is a low estimate for refurbishing converter station cooling systems.

In summary, while some elements of the converter station may be replaced or updated on cycles of 10 years or less, most of the costly equipment is expected to have a life of 30 years or more. Moreover, with proper maintenance most of today’s conversion equipment can have a 40 to 50 year life. The effects of discounting over such long periods of time diminish from the importance of life-cycle cost issues in the economics of HVDC technology. Therefore, converter life-cycle considerations should not weigh significantly against HVDC today.

3. FACT FINDING AND PROJECT KICK-OFF (Task 1)

BCTC is evaluating options to provide additional transfer capability on the ILM beginning in 2014. One of the alternatives BCTC is considering as an ac option for meeting this new transfer capability requirement is the construction and operation by 2014 of a new 500 kV ac single-circuit 50% series compensated transmission line from Nicola (NIC) to Meridian (MDN) Substation. This ac alternative, labeled 5L83, provides approximately 2100 MW of incremental thermal overload capacity. 5L83 was selected as the benchmark case for evaluating the technical and economic feasibilities of HVDC options in this study. The ac benchmark is projected to be capable of providing 2100 MW of incremental thermal overload transmission capacity if voltage support is added to allow operation at thermal limits. To measure the potential applicability of HVDC, one must first identify HVDC options that can be directly compared with 5L83.

Additional facts that have to be taken into account by the DCI team include:

1. While an HVDC line that would be built in place of an ac 5L83 is an obvious and essential point of comparison of ac and dc, BCTC also wishes to have an evaluation of the potential benefit of converting existing ac lines to HVDC:
   a. 5L81 and 5L82 are particularly interesting candidates since converting them would increase the transfer capability of the same corridor under consideration for the 5L83 ac alternative; and
   b. For reference and to ensure a comprehensive analysis, other line conversions should be addressed at least qualitatively.
2. Most of the right-of-way necessary for 5L83 has been secured or can be secured and is to be assumed adequate for an HVDC line in place of 5L83.
3. While there may be some differences in the reactive requirements of ac and dc options for 5L83, the analysis is to present only HVDC reactive needs that would significantly affect a cost comparison or would have implications for substation space requirements. A significant aspect of an HVDC option is that each terminating converter requires its own dedicated reactive power support totaling approximately 58% of the dc power being transferred. This reactive power supply is an integral part of the converter configuration and usually consists of fixed and switched ac harmonic filters and mechanically switched reactor and shunt capacitor banks. Levels of compensation are switched in and out in discrete steps to approximately balance the reactive power requirement of the converters as dictated by the dc power schedule. For this study, the reactive power requirements of the dc converters are considered part of the HVDC transmission equipment and included in the HVDC line cost. In other words, the HVDC converters and their associated reactive equipment are generally controlled to operate

at or near unity power factor. Other substation reactive supply equipment thus need only accommodate the needs of the ac transmission lines.

4. Because this is an initial examination of the potential of HVDC to compete with a new ac circuit, BCTC has requested planning level cost estimates. The estimates provided in this report are judged to be within a -10% to +20% margin of error. That is, in a best-case result our estimates may be high by 10%. Also, where appropriate, a 20% contingency should be added to cover the possibility of our estimates being low.

5. Losses are a significant cost item and are to be addressed in the analysis. BCTC has procedures to evaluate the cost of losses and is most interested in knowing the system loss savings that can be expected from use of HVDC.

6. Staging investments is of interest:

    a. With staging, equipment is installed only when necessary to provide the required transmission capacity expansion or to reduce losses economically.

    b. For the ac 5L83, substation equipment would have to be installed by 2014 whereas the addition of reactive supply and series capacitors on 5L83 could be staged to incrementally meet annual increases in the demand for transfer capability until additional transfer capability is required.

    c. With HVDC, costly converter station equipment can be installed only when needed and then upgraded on an as-needed basis.

    d. While the losses-reduction benefit of a fully capable HVDC line in 2014 may make staging less attractive, BCTC would like at least a qualitative assessment of HVDC staging options.

4. SCREENING ALTERNATIVE HVDC SOLUTIONS (Task 2)

There are two obvious HVDC approaches to meeting future ILM transfer capability needs:

1. Constructing an HVDC version of 5L83; and
2. Converting 5L81 and/or 5L82 to HVDC.

These candidate solutions do not require screening and were, therefore, passed on to the full analysis under Tasks 3 and 4.

Among the lines that could also be converted to HVDC or replaced with higher capacity HVDC lines are all of the 500 kV circuits served by the Kelly Lake (KLY) Substation. They include 5L42, and 5L41 and 5L40. For instance, 5L41 and 5L40 could be concatenated to form a single longer HVDC line. However, doing so would require an alternate ac feed to the Clayburn substation which would drive up the cost of such an option. Additionally, converting lines out of KLY to HVDC was judged to provide no more ILM capability than would conversion of 5L81 and/or 5L82. Hence no analytical analysis was performed for these options..

An HVDC 5L87 would primarily provide the ability to control the amount of power routed between KLY and NIC. This option could allow maximum use of 5L41 and 5L42 out of KLY and 5L81 and 5L82 out of NIC, but would not increase the ILM transfer capability substantially. Additionally, although installing adjustable series compensation or a phase angle regulator in the existing 5L87 ac line could provide similar benefits, BCTC indicates that neither has yet proven to be economically justifiable. These considerations rule out further consideration of the more costly HVDC conversion option.

Several lower voltage lines were examined briefly to ensure no attractive conversion opportunities were overlooked. These included 2L1, 2L2, and 3L2. The potential for increasing the thermal capability of these lines by conversion to HVDC is discussed in Appendix D. These circuits serve “load taps” at multiple points along the ROW and are expected to provide additional load tapping capability in the future. Load taps do not rule out conversion to HVDC, particularly where there are two circuits and one can be dedicated to HVDC conversion. However, they can increase the difficulty of converting lines and service reliability to customers on load taps could drop excessively. It is also possible to replace existing lines with new HVDC lines containing a 230-kV ac under-build. This option was judged to be more costly and to provide less new ILM transfer capability than conversion of 5L81 and/or 5L82 and therefore was not considered further in this study.

Appendix D presents an initial analysis of the potential thermal ratings of converted lines. The analysis clearly shows that the conversion options that are capable of achieving the 2100 MW transmission expansion target are limited to 5L81 and/or 5L82. Hence, no other conversion alternatives were further considered.

5. TECHNICAL FEASIBILITY OF HVDC SOLUTIONS (Task 3)

This section presents an analysis of the technical feasibility of two HVDC approaches for providing 2100 MW of additional ILM thermal overload transfer capability by 2026:

1. Constructing a new 5L83 as an HVDC circuit; and
2. Converting either 5L81 and/or 5L82 to HVDC.

DCI's assessment of the technical feasibility of the new line and of the conversion options is presented below. Cost issues and the competitiveness of the HVDC alternatives with each other and with the EHV AC 5L83 benchmark case is discussed in Section 6 under Task 4. Appendix F gives the single line diagrams for the alternatives discussed in this section.

Constructing a New 5L83 HVDC Circuit

DCI analysis indicates that certain HVDC versions of 5L83 can be technically effective in meeting ILM transmission expansion needs.

Specification of the Candidate Designs

As a new line, an HVDC 5L83 can be designed to provide the required level of thermal capability. HVDC circuits are typically built to higher ratings than competing ac alternatives. For the purposes of this analysis, we have determined a bipole rating of 2200 MW and a tripole rating of 3000 MW for the 2100 MW increase in ILM thermal overload transfer capability. Both options could be designed for early operation at lower ratings and later upgraded when needed. These ratings are practical in that N-1 pole-outages will have less impact on the ILM than comparable N-1 outages of the substitute ac circuits.

A new HVDC 5L83 could be built as an ac line but insulated for HVDC. This allows initial operation at 500 kV ac, followed by conversion to bipole when there is need for more transfer capacity. As a bipole, two conductors would form one pole and a third would act as the other. A design with three-phase positions costs more than one with two poles but it may defer installing HVDC converters, reduce losses and improve reliability. Also, such design facilitates single phase conductor switching that can be used to maximize power transfer in a temporary two-phase configuration during certain outages. Though unlikely, reverting to ac operation could be considered as well. Finally, having three conductors might also allow upgrading to tripole beyond 2026.

Technical Feasibility of the Candidates

Table 1 provides DCI's planning-level specifications and operating requirements and capabilities for two 5L83 HVDC design options addressing the 2100 MW thermal overload capability benchmark. The focus of the table and the discussion below is on bipole (conventional) HVDC. However, references to tripole are made when it is deemed the information supplied could influence BCTC's investment decisions between now and 2026. For instance, as stated earlier, one of the benefits of constructing 5L83 with three conductors is the possibility of eventually attaining economic tripole operation.

Table 1: Planning-Level Specifications and Capabilities for Two 5L83 HVDC Options for a 2100 MW increase in ILM Thermal Overload Transfer Capability

Comparison Item	Bipole (Two Conductors)	Bipole (Three Conductors)
Voltage	+/- 500 kV	+/- 500 kV
Conductors	Four-conductor bundle (337.9 mm^2)	Four-conductor bundle (337.9 mm^2)
Conductor Spacing	460 mm	Same as existing ac (460 mm)
ROW Width	Same as existing AC	Same as existing ac
Line Configuration	See Figure 2 below	Same as existing ac
Line Thermal Rating (limited by converters, normal rating shown, continuous overload 10% higher, sending end power levels shown)	2014: 2200 MW 2020: 2200 MW 2026: 2200 MW 2032: 2200 MW	2014: 1400 MW (ac) 2020: 2200 MW (dc bipole) 2026: 2200 MW (dc bipole) 2032: 3000 MW (dc tripole) 2038: 3000 MW (dc tripole)
ILM Transfer Capability (N-1)	6,900+ MW	8,300 MW
Reliability Adequacy (N-2)	Yes	Yes
Converter Losses	0.035% of power flow (variable) 0.035% of converter rating (fixed)	0.035% of power flow (variable) 0.035% of converter rating (fixed)
Line Losses at rated load (see Task 4 for ILM losses)	91 MW (Figure E-1 Appendix E	76 MW Appendix E
Short-circuit Adequacy at NIC	Yes	Yes
Short-circuit Adequacy at ING	Yes	Yes
Reactive Power Equipment Requirement at each converter	1275 MVAr of filters/ mechanically switched capacitors (MSC)	2014: 0 MVAr of filters 2020: 1275 MVAr of filters/MSC 2026: 1275 MVAr of filters/MSC 2030: 1740 MVAr of filters/MSC 2036: 1740 MVAr of filters/MSC
Substation space required at NIC	Yes see Figure H-1 in Appendix H	Yes see Figure H-1 in Appendix H
Substation space required at ING	Yes see Figure H-3 in Appendix H	Yes see Figure H-3 in Appendix H
Availability of Power Flow Control & Stability	Yes	Yes

Voltage

The operating voltage for a new bipole HVDC 5L83 is arbitrarily set at 500 kV for the purposes of reviewing candidate HVDC options. This is the same voltage selected for converting 5L81 and 5L82; a limit determined by gradients pertaining to existing 5L81 and 5L82 conductor configurations. If an HVDC 5L83 is found to be a credible option, the voltage level should be optimized. However, because 500 kV is the highest HVDC voltage applied in North America, higher voltages have not been part of this assessment.

Conductors

Each pole of the bipole HVDC 5L83 is assumed to consist of a bundle of four 337.9 mm^2 AACSR conductors. The continuous current rating for such conductor configuration should be similar to ratings assigned to existing ac circuits 5L81 and 5L82; i.e., about 3,300 amperes for winter and 2,260 amperes for summer.

Conductor Spacing

The spacing for a bipole HVDC 5L83 is assumed to be 13.4 meters. If an HVDC 5L83 is built in the benchmark's ROW, it will have conductor spacing comparable to what is currently envisioned for an ac 5L83 (i.e. 13 meters). Figure 2 gives simplified sketches of the structure of typical 500 kV HVDC (derived from Manitoba Hydro tower Type "C") and EHV AC (BCTC typical single circuit "Delta" towers. Shield wires are not applied.

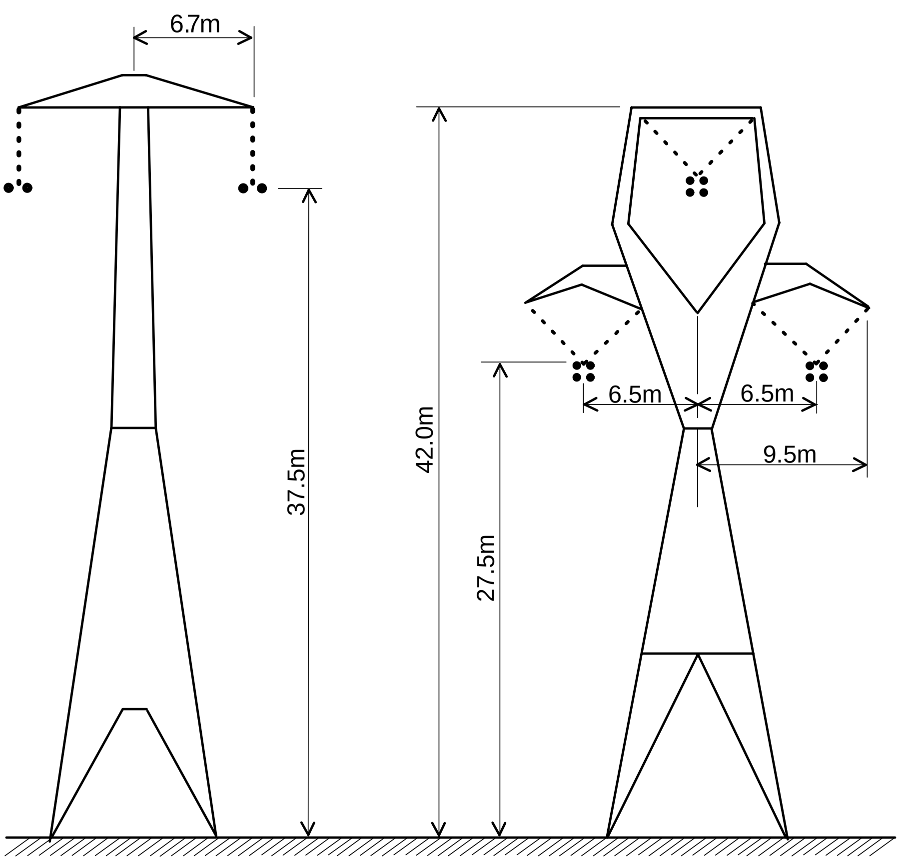


Figure 2: Tower Structures For 500 kV HVDC and EHV AC Circuits

ROW Width

A 500 kV HVDC bipole 5L83 would use slightly less ROW than a flatly configured 500 kV ac circuit and a similar amount in comparison with a delta-configured 500 kV ac tower.[4] A delta configured ac tower compared with a dc tower of similar voltage as shown in Figure 2 indicates no ROW benefit for an HVDC bipole circuit compared to an ac circuit of similar voltage. However, an HVDC circuit has greater power transfer capacity than an ac line of similar voltage particularly when longer distance transmission is necessary. At 500 kV, an HVDC line can be designed for 3000 MW. Achieving such transfer capability with EHV AC would require two 500 kV ac circuits and nearly double the amount of land needed for the transmission ROW.

BCTC indicates that ROW for 5L83 has already been secured or is not problematic. With this ROW considered to be available for 5L83 as an ac line or a bipole HVDC line, ROW considerations are not a factor in the comparison of ac and dc options to add up to 2100 MW of thermal overload capability to the ILM. However, a planning horizon reaching beyond the current forecast need for transfer capability might indicate some added value to HVDC in that HVDC could potentially defer a future new ROW in the ILM. To do so, the HVDC overhead line and associated converter stations would need to be designed to accommodate an upgrade beyond the present forecast need; perhaps the 3000 MW indicated above. If a second 500 kV transmission line has to be advanced in time because of the lower ILM power transfer limit, then there are staging options that can be considered:

1. Install an ac 5L83 transmission line in 2014, perhaps without series capacitors. At some later date convert it to bipole, and then to tripole with a total rating of over 3,000 MW. This would require providing an appropriate conductor and that the line be initially constructed with dc insulators.
2. Install a dc bipolar transmission line for 5L83 with 1,600 MW converter stations at each end in 2014. At some later stage, add parallel valve groups to raise the transfer capacity of the line to 3,200 MW.

The cost of accommodating a future upgrades beyond present forecast needs was judged to be greater than the long-term potential benefit of a deferred ROW and so was not considered further in this analysis.

A similar argument and discussion could be applied to HVDC use and ROW requirements beyond the ILM. For instance, if generation were being contemplated for the Peace River or Colombia River north and east of the ILM respectively, there might be advantage in combining transmission for such project with an ILM upgrade. The result could be a much longer HVDC (relative to 5L83) HVDC line that runs directly from a point near that new generation to MDN or Ingledow (ING). A longer HVDC line might be competitive or advantageous with ac options to achieve the same ILM upgrade and generation outlet service.

[4] The ROW requirements for the HVDC and EHV AC 500-kV towers should range from 50 to 60 meters.

Line Configuration

Line configuration was assumed to be a factor in the feasibility analysis to the extent that 5L83 could be constructed with either: (i) two conductors and operated immediately as HVDC, or (ii) three conductors and initially operated as an uncompensated ac line and later converted to HVDC. The cost differences between these two options could b substantial.

Thermal Ratings of Lines and Converters

A two-conductor bipole HVDC 5L83 could have an ultimate thermal rating of 2100 MW with a continuous overload capability of 2200 MW. In the first year of operation, the rating could be much less. As the ILM transfer capability requirements grow, converters can be added or upgraded to increase equipment rating appropriately.

A three phase-position conductor 5L83 with pre-installed HVDC insulators could be initially operated as an uncompensated ac line to enable BCTC to defer investing in HVDC converters by several years. The initially limited rating would be eventually raised to a level comparable to a two-conductor bipole line, or somewhat higher if a tripole configuration is adopted.

For the purposes of this study, the rating of an HVDC 2100 MW incremental thermal overload capable 5L83 in 2026 was defined on the basis of the following considerations:

- Post N-1 ILM transfer adjustment is no greater than required by an ac 5L83 circuit.
- Special controls are required to adjust the HVDC loading following the most severe N-1 events.
- Post N-2 ILM transfer adjustment is not greater than required for an ac 5L83 circuit.

These criteria result in an HVDC rating of 2100 MW at the sending end and an inherent continuous overload capability of 2200 MW. However, If HVDC proves to be a potentially credible alternative to an ac 5L83, then the aforementioned ratings would have to be re-examined using a more rigorous analysis.

ILM Transfer Capability

An initial analysis was performed to determine the HVDC 5L83 line rating that would produce a 2100 MW increase in the ILM's thermal overload capability. The result is a least-cost HVDC alternative that could produce a 2100 MW increase in thermal overload capability by 2026 or earlier. The HVDC continuous rating is 2200 MW and is directly comparable with the 1836 MW continuous and 2425 MW one-hour ratings of the ac 5L83. Power flow simulations indicated a new two-conductor bipole 5L83 ensured the attainability of an ILM thermal overload capability of at least 6,900 MW under N-1 criteria in 2026. The ILM thermal overload capability that could be achieved with a three-conductor tripole version of an HVDC 5L83 exceeds 8,300 MW beyond 2026. As previously stated, the selected HVDC 5L83 ratings are not necessarily optimal. If HVDC were found to be a plausible option, BCTC will need to do further analysis to optimize HVDC equipment and line ratings.

Reliability Adequacy

The ILM incremental thermal overload capability discussed above reflect careful consideration of the N-1 and N-2 reliability criteria. This consideration was sufficient for the purposes of this initial investigation. Given the significant differences between ac HVDC operation and HVDC design options such as metallic return and short-time-rated ground electrodes, a more rigorous interpretation of the applicable criteria and HVDC performance options should be undertaken before finalizing an HVDC choice. A more rigorous interpretation of the criteria should involve treatment of HVDC auto adjustment controls, applicability of manual adjustments, speed of generation curtailment to prepare for the next N-1 event and similar considerations. Likewise, system adjustments to accommodate N-2 events will be important.

Converter and Line Losses

Losses for the 500 kV HVDC bipole 5L83 line selected for this analysis consist of three components:

- Variable converter losses of 0.35 percent of line loading
- Fixed converter losses of 0.35 percent of converter rating at each terminal
- Line losses that are a function of line loading

Assuming an HVDC line loading equivalent to the N-0 loading of the benchmark ac 5L83 transmission line of 1717 MW at maximum ILM power transfer in 2026, the three loss components add up to 61 MW at full loading. This estimate appears to compare well with the benchmark ac 5L83 whose losses amount to 82 MW for the same level of loading (Figure E-1, Appendix E). However, a more realistic comparison must be carried out on a system-wide basis since in a predominantly ac grid line loading are largely determined by Kirchoff's and Ohm's laws with a limited role for power-flow management by dc circuits. ILM losses are considered in detail in Task 4 and Appendix E.

Short Circuit Adequacy

Short-circuit capacity at NIC is adequate for operating an HVDC 5L83 under normal and single line-out conditions. Both ING and MDN have substantial short-circuit capability and will not impose constraints on operating 5L83 as an HVDC line.

Reactive-Power Equipment Requirement

An HVDC 5L83 rated at 2000 MW would require about 800 MVAr of filters (or 40 percent of converter full load rating). These filters would supply all or most of the HVDC line reactive requirements when line loading is below approximately 70 percent of its rating, and will provide about 40 percent of the line reactive requirement when it is operating at its continuous full rating. To maintain the converter at approximately unity power factor, mechanically switched capacitors and reactors are normally applied, including switching of redundant ac filters. The maximum size of a reactive power switched element should be such that the resulting voltage step does not impact nearby customers. Further details are provided in the discussion of ac and dc reactive power requirements in Section 6 below.

Substation Space Requirement

A physical matter related to building 5L83 as an HVDC line is space availability for the converters and associated cooling, compensation, and filter equipment at NIC and MDN. A 2000 to 2100 MW HVDC converter station will require about 17.3 acres of land for each line terminal. A 3,000 MW converter station requires approximately 22 acres at each end whereas an 1800 MW converter would require approximately 15 acres. These space requirements imply compact designs without the use of gas insulated equipment. However, there is a degree of flexibility in how an HVDC substation can be laid out that may facilitate fitting the converters into available area as in the case of the ING Substation. Appendix H provides preliminary information about land requirements and availability at the ING, MDN and NIC Substations.

Staging Options

A new HVDC two-conductor bipole 5L83 would be energized in 2014 as an HVDC line, but could have upgradeable converters to take line capability up to its full rating in stages of one pole at a time as the need arises. Staging converter additions could be managed to minimize total losses. This means that upgrades might occur before line capability becomes fully usable.

A new HVDC three-conductor 5L83 would be energized as an ac circuit and have converters added later when additional capability is needed. Alternatively, BCTC could continue operation in an ac mode and add series capacitors if switching to HVDC transmission is found to be less attractive at the time the upgrade is needed (i.e., some time beyond 2014). If HVDC is the choice, initial converter arrangement would be bipole. Bipole converters could be upgraded as needed to follow capability requirements. Eventual conversion to a tripole configuration would provide additional thermal transfer capability of about 37% above the desired increased level achieved with a bipole.

Converting Existing Lines to HVDC

In this section we examine the technical feasibility of converting 5L81 and/or 5L82 to HVDC to meet ILM transfer capability needs from 2014 through 2026 and beyond. Our analysis indicates:

- Converting these lines into bipole 500 kV HVDC circuits requires confirmation of substation space availability and could lead to violation of important reliability criteria; and
- A tripole configuration for the converted lines will not lead to violating reliability criteria with the help of a remedial action system but may require the acquisition of additional land to house converters and associated equipment.

Specification of the Candidate Designs

Determining the options to consider for converting 5L81 and 5L82 is dictated primarily by three factors:

- The incremental thermal capability that can be provided to the ILM without violating applicable reliability criteria;
- The need to minimize the cost of the required investment; and
- Space availability for converters at NIC and ING and/or MDN.

To achieve the required increase in the ILM thermal capability at an acceptable cost and without degrading grid reliability, we ruled out conductor changes. Consequently, line modification must be limited to replacing existing ac insulators with HVDC insulators. Ruling out conductor changes has essentially disqualified bipole conversion of 5L81 and 5L82 because detailed simulations showed that:

- Converting 5L81 and or 5L82 to bipole HVDC leads to overloading of some lines – and in particular 5L42 – beyond their summer steady-state conductor capability in 2026 for non-contingency operation.
- Conversion of both 5L81 and 5L82 to bipole at 2,152 and 2,264 MW ratings, respectively, would cause flow through 5L82 to exceed 2,100 MVA under non-contingency conditions when its continuous summer rating would be 1,961 MVA. (See Tables D-2 and D-3 of Appendix D). Conversion to bipole thus does not achieve the desired 2100 MW increase in ILM thermal overload capability.

Bipole conversion options were not considered further in this study.

Tripole HVDC was included in this assessment of converting 5L81 and 5L82 to dc inasmuch as: (1) it appears to be only way in which HVDC conversion could match the transfer rating increase expected from a new 500 kV circuit, and (2) its being the subject of investigation by EPRI and other utilities may cause potential challenges as to the completeness of any evaluation of the competitiveness of HVDC alternatives with proposed EHV AC investments.

It is possible to minimize the costs of tripole conversion investment by staging the installation of the required converters. This can be accomplished by converting 5L82 to tripole in 2013 or 2014, and 5L81 to tripole some years later – around 2020. The exact timing of implementation would have to be determined through additional studies. In 2026 and under peak power-flow conditions, 5L82 and 5L81 would be loaded to the steady-state conductor limits of 2,600 MW for 5L82 and 2541 MW for 5L81 for the 2100 MW ILM thermal overload transfer expansion. (See Appendix D).

Technical Feasibility of the Candidates

The results of the investigation of the conversion options are presented in Table 2 below and the discussion following it. The analyses behind these conclusions are documented in the indicated appendices.

Table 2: Planning-Level Specifications and Capabilities for 5L81 and 5L82 HVDC Conversions for a 2,100 MW increase in ILM thermal overload transfer capability.

Comparison Item	5L82Tripole	5L81 Tripole
Voltage	+./- 430 kV; see text below	+/- 430 kV; see text below
Line Thermal Rating (limited by converters, normal summer rating, continuous overload rating 10% higher)	2014: 2668 MW (3870 MW overload)	2014: No construction 2020: 2536 MW (3870 MW overload)
ILM Ultimate Transfer Capability (N-1) (see discussion in the text below)	6900 MW	8300 MW
Reliability Adequacy	No N-1 overload No N-2 with RAS	No N-1 overload No N-2 with RAS
Total Converter Losses (0.35% of continuous loading one end for variable, 0.35% of rating for fixed losses)	39 MW at 2600 MW 54 MW at 3870 MW	38 MW at 2541 MW 54 MW at 3870 MW
Line Losses	121 (Appendix E, Figure E-1)	118 (Appendix E, Figure E-1)
Contingency based Short-circuit Adequacy	17,300 MVA at NIC 12,400 MVA at MDN	17,300 MVA at NIC 16,500 MVA at ING
Reactive Power Equipment Requirement	1,800 MVAr of filters, 450 MVAR of MSC	1,800 MVAr of filters, 450 MVAR of MSC
Substation space required at NIC or MDN	Problematic (see Figure H-1 in Appendix H)	Problematic (see Figure H-1 in Appendix H)
Substation space required at MDN or ING	Problematic (see Figure H-2 in Appendix H)	Adequate (see Figure H-3 in Appendix H)
Power Flow Control capability	Yes	Yes
Staging Options	No	Yes (Convert 5L81 to tripole in 2020)

Voltage

Voltage selection for conversion to HVDC is based on conductor surface voltage gradients and the insulation capability of the towers (as discussed in detail in Appendix D). The tripole configuration imposes a higher than normal conductor surface gradient on shield wires. This is particularly limiting in the case of 5L81 and 5L82 which have relatively small shield wires for a relatively short section of line near the substations. The tripole voltage of 430 kV, assumed for this study, might require replacement or relocation of these shield wires, the cost of which, though modest, was not explored in this study.

The post-conversion dc electric field at ground level was also examined for the 5L81 and 5L82 configurations. Calculations showed that a minimum clearance to ground of 14 meters would produce an electrostatic field of approximately 15 kV/M one meter above the earth's surface with the tripole configuration; less for the bipole. This is probably satisfactory but is another aspect of dc operation that should be examined in more detail if the conversion option is pursued – particularly if actual minimum clearances are less than 14 meters.

Although tripole technology uses no equipment, ramp times, or control technology that are not already in wide use in bipole and monopole systems, those technologies have yet to be aggregated and demonstrated in the tripole configuration. It is prudent therefore to postpone tripole application as a primary option for 500-kV transmission until it is demonstrated at least at a lower voltage level.

The existing conductors are assumed to remain unchanged for all dc conversion options. Existing ac insulators are assumed to be replaced with HVDC high-creepage units.

Less stringent sag constraints with HVDC will allow extending the existing string length somewhat, thus increasing allowable HVDC voltage above the line-to-ground crest of the former ac voltage.

Finally, the dc voltage capability of existing ac lines was based on best-estimates only and was not optimized.

Conductor Spacing

Existing phase spacing was assumed to be unchanged.

ROW Width

Converting existing lines to HVDC and not using ROW for a new 5L83 transmission line may allow closer positioning of future adjacent transmission lines or delay the need for an additional transmission line until beyond 2026.

Line Configuration

Line configuration would not change beyond replacing insulators with longer creep distance.

Line Thermal Rating and Converter Thermal Ratings

Only continuous summer ratings for the conversion of 5L81 and 5L82 were considered because they are lower than the winter values and must support higher ILM loadings in the spring and summer months. The following converter ratings were considered for the purposes of this study:

- For 5L81: 2,150 MW continuous summer normal rating and 3,870 MW for one-hour summer overload
- For 5L82: 2,260 MW continuous summer normal rating and 3,870 MW for one-hour summer overload

Upgrading both 5L81 and 5L82 to tripole at 2,536 MW and 2,668 MW respectively (with 3,870 MW one hour overload, which is a continuous rating insofar as the tripole converters are concerned) increases thermal overload capability of the ILM to 2,100 MW. It is not attractive to rate the tripole converters at 3,870 MW for a one hour overload capability if the continuous conductor summer thermal rating is much less at 2,536 MW and 2,668 MW respectively. HVDC converters would have to have a continuous overload rating of 3870 MW because their short-time overload capability is relatively negligible in this context. Details of the analysis and of the estimated thermal capabilities are presented in Appendix D.

ILM Transfer Capability

Power flow analysis of converting 5L81 and 5L82 to dc circuits shows that requirements can be met only if tripole technology is used. The additional power transfer capability of tripole is needed to allow the grid to operate within its one-hour overload capabilities under N-1 contingency conditions. The most significant limiting transmission line in this regard is 5L42 between KLY and Cheekye (CKY) Substations. If the tripole ratings of the converters were to allow the application of the summer one-hour overload rating of the conductors (3870 MW), then the total transfer capability of the ILM could match what is expected from a new ac 5L83 transmission line; namely, 6,900 and 8,300 MW for 5L82 and 5L81, respectively (see Table 3 below).

For an N-2 situation represented by loss of either the 5L81 or 5L82 circuit, a remedial action system must be used to quickly drop or ramp down generation for 2026 maximum power transfer conditions. Based on a power flow assessment, a reduction of generation amounting to 500 to 600 MW is required to reach the one-hour capacitor overload level of 5L42; the critical line in this case.

The ILM thermal overload capability provided by converting 5L81 and/or 5L82 is shown in Table 3 for the condition where 2,100 MW in ILM thermal overload transfer capability is required.

Table 3: Total Transfer Capability from Conversion

	5L82 (Stage 1) 2014-2020	**5L81 and 5L82 2021-2026**
Tripole	6,900 MW	8,300 MW

Reliability Adequacy

When 5L81 and 5L82 are both converted to tripole with continuous-operation ratings of 2,536 and 2,668 MW, respectively for the 2,100 MW increase in ILM transfer, and tripole one-hour delivery rating of 3,870 MW, no overloading is expected to develop on any transmission line in 2026, either for steady state or N-1 contingency conditions. (See Table D-3, Appendix D for details.) For the N-2 condition where the entire circuit of either tripole is out of service, the remaining tripole can operate for one hour at the 3,870 MW level. Under these conditions 5L42 becomes loaded to 2300 MVA, which exceeds the summer one hour conductor rating of 2165 MVA. This would unfortunately require remedial action to bring the loading of 5L42 within the one-hour limit. However, since the 5L42 is the dominant remaining circuit in the ILM interface, the needed generation runback or unit dropping would not be more than the 500 to 600 MW mentioned above.

Converter and Line Losses

The loss characteristics of 500 kV ac lines and new and converted HVDC lines are detailed in Appendix E, Table E-1. Elements of that analysis are presented here for the conversion of 5L82. The analysis for 5L81 is essentially the same. An HVDC 5L82 will have losses of approximately 0.7 percent of the MW loading in the converters. Additionally, line losses will be approximately 121 MW at the continuous normal-summer rating of 2600 MW for a converted 5L82. Total converter station losses would be 39 MW. A change of conductors on 5L82 and 5L81 is not likely to be justified; hence these losses are not subject to optimization beyond establishing a maximum continuous normal rating for the converters. Also, we did not consider the potential loss-minimization benefits that could be gained from the grid operator's ability to control flows over dc lines.

While loss minimization will be effective, the benefit will be modest and will shift the comparison of 5L83 and dc options in favor of the dc options only if the comparison is very close from cost and reliability standpoints. If the comparison is close and lesser differences must be considered to make a decision, then the operational loss benefits should be examined and included.

Line losses will be approximately 118 MW at 5L81 converted to tripole operation at 2,450 MW for the lower ILM thermal transfer levels with total converter station losses of 35 MW. Losses on 5L82 converted to tripole operation will be similar.

Short Circuit Adequacy

Converting 5L81 or 5L82 will reduce short-circuit levels at NIC. The lower short-circuit level is adequate for operating either 5L81 or 5L82 as an HVDC line as indicated in Appendix G

In the worst case, with both lines converted to HVDC, a forced outage of 5L87 would cause the NIC short-circuit level to drop to where it would no longer adequately support the two 3,870 MW converters fed by this station. While even lower short-circuit level conditions could occur, they do not constitute a credible design condition The low short-circuit fault level at NIC for the two large converters requires installing synchronous condensers or STATCOMs at that location to ensure reliable commutation and ac voltage control during transient conditions. Using an SVC in this situation would in fact lower the effective short-circuit capacity due to the parallel combination of the effects of its shunt capacitance and largely inductive system short-circuit impedance. Determining the total rating of the synchronous condensers or STATCOMS needed at the NIC Substation for the two HVDC converters requires a detailed study beyond the scope of this project. However as a rough estimate, 2,000 to 3,000 MVAr of dynamic compensation could be needed, adding significantly to the cost of the HVDC conversion option.

The short-circuit levels at MDN and ING are provided in Appendix G. Credible ac circuit outages will not drop these short-circuit levels at these substations below what is required for successful commutation of converters on 5L81 or 5L82.

Reactive Power Equipment Requirement

Each HVDC converter requires filters and compensation with MVAr capacity equal to about 50 percent of the HVDC line rating. Using the summer continuous N-1 overload rating as a basis for estimating the needed reactive power support, we project filter requirements of 1,290 MVAr for each tripole application.

Substation Space Requirement

Conversion of 5L81 and 5L82 will require approximately 24 acres of land for 3,870-MW rated converters, transformers, and converter cooling and reactive equipment at each terminal as well as a second circuit breaker bay at each terminal at ING and MDN. With both tripoles terminating at NIC , 48 acres will need to be prepared.

NIC, MDN and ING layouts are provided in Figures H-1, H-2 and H-3 of Appendix H.

Power Flow Control

The benefits of HDVC line power controllability discussed in section 2 would apply. Controls and operating practices to make use of this controllability would be necessary.

Staging Options

Staging options for converting 5L81 and/or 5L82 are limited to scheduling the rating of the HVDC equipment. Converters and filters could be installed at lower capacity and designed for expansion as needed in one or two stages. One stage of expansion may be economically attractive. Additional stages would likely not be useful. One such strategy could involve converting 5L82 in 2014 and delaying the conversion of 5L81 by several years; possibly to 2020. In both cases staging of converter capacity may be found attractive.

6. COMPARING CANDIDATE SOLUTIONS (Task 4)

In section 5, we have reduced the number of HVDC options that might be used to meet a 2100 MW ILM thermal overload capability expansion to the four options found to be worthy of consideration:

1. A two-conductor HVDC line in place of 5L83 utilizing the same corridor
2. A three-conductor 5L83 without series capacitors and with staged conversion to HVDC
3. Conversion of 5L81 or 5L82 to HVDC
4. Conversion of both 5L81 and 5L82 to HVDC

In this part of the report, we present our assessment of the capital costs of these alternatives. Section 6 also provides a comparative analysis of the costs and capabilities of the four HVDC solutions along with the ac benchmark case, 5L83.

Comparison of Capabilities

As discussed in detail blow, an HVDC line and a staged 5L83 conversion (starting with a dc-insulated version of the benchmark 5L83 without the series capacitors, energizing it initially as an ac line and later converting it into tripole) represent the two HVDC alternatives that could match the capabilities of 5L83 with its full compliment of the series capacitors. Converting 5L81 and 5L82 to bipole HVDC was found to be less effective. The inability to utilize one conductor bundle during the bipole operation of 5L83 and of bipole-converted 5L81 and 5L82 severely limits the HVDC contribution to ILM thermal overload capability. Tripole overcomes this barrier and does provide the required 2100 MW of incremental thermal overload capability by converting either 5L81 or 5L82. However, this option has contingency limitations as do the 5L81 and 5L82 bipole conversions. Moreover, as stated above since tripole is not a proven technology it is not presented here as a contender at this time. An HVDC line in place of 5L83 and the staged 5L83 conversion alternatives were found to be the most effective HVDC options.

Line Thermal Ratings

See Appendix D.

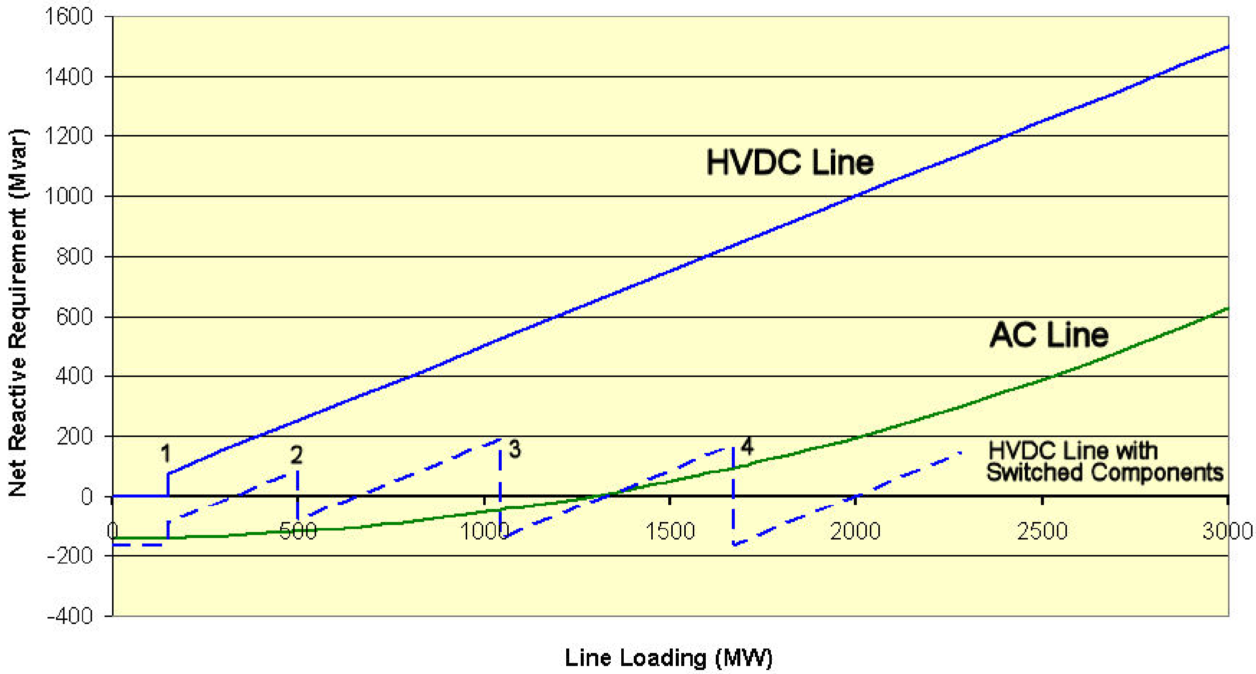
ILM Thermal Capability & Staging Options

Both conversion of existing ac lines to HVDC and construction of a new HVDC line in place of 5L83 offer multiple staging options that can meet interim requirements and defer investment.

Reactive Power Requirements

An HVDC 5L83 will require more reactive power than an ac 5L83. The difference is shown in Figure 3 for one end of the line. However, an HVDC line will also require filters that will supply varying portions of its reactive power requirement in the range 50-80%. The remainder will come from blocks of mechanically switched reactor or capacitor banks adjacent to the filters and also associated with the HVDC equipment. The switched steps are approximately as shown by points 1, 2, 3 and 4 in Figure 3. Where necessary, the steps can be smoothed with an SVC or STATCOM to keep the operation of the converters closer to unity power factor.

Figure 3. Comparison of HVDC and series compensated 500 kV ac transmission line reactive requirements.



As indicated by Table 4, reactive power requirements were found to increase for the MDN, ING, NIC and KLY . The observed increases reflect the expected rise in ILM power flow under the various studied options. It should be noted that the values shown in Table 4 do not include reactive power that will be required for the collecting system north of the ILM interface, nor does it include the additional MVArs that the Lower Mainland system will need to receive the power. Similarly, the HVDC options are assumed to include filters and the indicated reactive levels are net of the filters. The estimated reactive power requirements are intended to maintain ac voltage above 1.0 per unit at the identified 500 kV substations and below 1.05 per unit for selected contingencies. The actual determination of reactive power needs and how they would be met involves a very detailed study that is beyond the scope of this project.

Table 4: Substation Reactive Power Requirements for the Competing ILM Reinforcement Scenarios when ILM Thermal Overload is Increased by 2,100 MW

Alternatives	2014 (MVAr)					2026 (MVAr)				
	MDN	ING	NIC	KLY	Total	MDN	ING	NIC	KLY	Total
Base Case 5L83 AC 50% series compensated	520	350	130	-200	800	900	750	380	200	2230
HVDC Alternative #1 - HVDC line on 5L83 corridor	380	230	400	60	1070	770	780	630	130	2310
HVDC Alternative #2- Stage 1 operating 5L83 ac without series capacitors	520	350	130	200	1200					
HVDC Alternative #2 - Stage 2 conversion to bipole dc						770	780	630	130	2310

The system reactive power requirements discussed in this section were derived from the 2014 and 2026 power flow cases provided by BCTC for this study. They reflected the ILM power flow requirements of 6,900 MW in 2014 and 8,300 MW in 2026 through N-1 contingencies. These contingencies included loss of BCTC transmission lines 5L40, 5L44, 5L81, 5L82, 5L45, 5L41, 5L42 and 5L87. In addition, the benchmark 5L83 as an ac or as the HVDC option was included in the contingency assessment.

The reactive power requirements in Table 4 are not identified as being dynamic, which requires either SVCs, STATCOMs or synchronous condensers or as being static, either fixed or mechanically switched. The determination of the exact reactive power demand and how it is supplied is beyond the scope of this study. However, the ING SVC was operating in these studies.

HVDC Alternative #1 would require about 270 MVAr more than an ac 5L83 line with series compensation (1070-800). Staging an HVDC line (Alternative #2) would increase reactive requirements to 1200 MVar during the time the line is operating ac (without series compensation). However, these additional capacitors would be required in the future in any event.

By 2026 the reactive requirements are little different among the alternatives.

Construction Outage Requirements

Construction outages will be required. For construction of a new HVDC line in place of 5L83, the construction outages should not be significantly greater than would be the case for an ac 5L83. Substation layout will have significant impact on construction outages. If converters for 5L83 can be installed without moving existing circuit breakers and buswork, substation construction outages should not be significantly greater than for an ac 5L83.

Conversion of 5L81 and 5L82 will involve more construction outages than will a dc 5L83. The construction outages will be more onerous in that they will involve existing lines without the benefit of a new line. However, line outages can be minimized by using hot-line techniques to change to ac insulators. Substation construction outages would exceed those required for construction of a new ac 5L83 line, but not significantly.

Losses

Table 5 provides estimates of system losses for 2014 and 2026 peak ILM-flows for the 5L83 2100 MW increased thermal overload case and the two HVDC options that could match its capabilities. The displayed values represent losses for the complete BCTC bulk system included in the model. However, because only the ILM has been changed or upgraded, all loss differences in the Table are differences on the ILM. For the dc options, each converter station was assumed to have 0.35 percent in fixed losses, and 0.35 percent of variable losses; both values are based on full loading of converter stations. HVDC line losses were not represented in the model but have been added and included in the table.

Table 5: Estimates of Peak-Flow System Losses for the Competing ILM Reinforcement Options

ILM Option	2014 Peak Losses (MW)	2026 Peak Losses (MW)	2014 Difference in Losses c/f Base Case (MW)	2026 Difference in Losses c/f Base Case (MW)
Base Case 5L83 AC	767	1001	0	0
Alternative #1 - HVDC line on 5L83 corridor	770	1003	3	2
Alternative #2 - Stage 1 operating 5L83 ac without series capacitors	777	-	10	-
Alternative #2 - Stage 2 conversion to bipole dc	-	994	-	-7

Table 6 provides only loss benchmarks for 2014 and 2026 for the 2,100 increased ILM thermal overload case. If a more precise comparison of losses is needed, either additional interim cases should be run, or the losses should be assumed to increase with the square of the ILM loading and thus be proportioned among intermediate years on this basis.

Comparison of Costs

Table 6 summarizes DCI's estimates of the costs of undertaking the ILM-reinforcement alternatives under consideration. The displayed values are in 2007 dollars and do not include interest during construction, the purchaser's engineering and administration costs, contingencies or additional reactive power compensation costs. The capital costs of the alternatives under study have been derived on the basis of published information from suppliers and CIGRE[5]. They include the contract price of the supplier for turnkey installation in 2007, site preparation expenses, project supplier's engineering and administration fees, and the costs of spares and ground electrodes. The exhibited estimates are budgetary within an accuracy of –10, +20 percent.

Table 6: Estimates of the Capital Costs in 2007 Dollars of the Competing ILM Reinforcement Options for the 2,100 MW Increase in ILM Thermal Transfer Level

ILM Option	NIC Converter ($\$M_{2007}$)	MDN Converter ($\$M_{2007}$)	Total ($\$M_{2007}$)
Base case 5L83 EHV AC (2100 MW)[6]	0	**0**	**0**
Alternative #1 - HVDC line on 5L83 corridor (2200 MW)	182.7	195.8	378.5
Alternative #2 - Stage 1 operating 5L83 ac without series capacitors (1400 MW)	0	0	-20
Alternative #2 - Stage 2 conversion to bipole (2100 MW)	182.7	195.8	378.5

The budget capital costs of Table 6 are derived from a number of sources including CIGRE [1] as well as responses from suppliers for recent specific projects. The capital costs are in Canadian dollars for turnkey installation in 2007 with an estimated -10%, +20% accuracy. They reflect the strengthening Canadian dollar in mid year 2007 and the noticeable increase in converter transformer prices in the first half of 2007. Please see Appendix I – Budget HVDC Station Costs for additional cost detail.

Findings

DCI analyses of the potential use of HDC technology to provide an 2100 MW incremental ILM thermal overload capability indicate:

- Constructing a new 500 kV HVDC bipole line in place of the contemplated 5L83 project using the same ROW represents a conventional HVDC technology alternative that could meet the requirements specified by BCTC;
- Constructing a 500 kV conventional ac circuit without series capacitors followed later by conversion to bipole dc also appears to meet the specified BCTC requirements;
- Total of substation equipment and line costs will be higher for a dc line in place of 5L83
- Assessing of the economic impacts of loss differences between the ac and the dc versions of 5L83 will not alter the cost gap between the ac and dc alternatives; and

[5] CIGE Brochure WG14.20: "Economic Assessment of HVDC Links," 2001
[6] Note that with a zero cost shown for 5L83 EHV AC, the line costs for the HVDC in this table are in addition to the 5L83 EHV AC series compensated benchmark circuit..

- Converting existing ac circuits into conventional bipole HVDC lines will not meet the ILM reinforcement requirements as stated by BCTC. Likewise, use of the new Tripole technology for these conversions will not meet reinforcement requirements.

7. Reactive Limited Options

Introduction

This section addresses HVDC options with reduced thermal capability. The reduction reflects continuous thermal rating and voltage stability limits of the ILM transmission grid. BCTC's preliminary studies indicated the capability provided by an ac 5L83 in 2014 will be limited to approximately 6750 MW continuous thermal rating and a 7120 MW voltage stability constraint. The voltage stability limit would be achieved after adding 470 MVAr reactive power support. In this section an HVDC option is defined to provide at least 6750 MW of capability and 7120 MW of capacity, while requiring less than 470 MVAr of new shunt compensation in the ILM ac system.

The 6750 MW capability represents a 1750 MW increase over the current 5000 MW continuous capability of the ILM grid. The 7120 MW limit represents a 1320 MW increase over the current 5800 MW ILM voltage stability limit.

New HVDC Line in Place of 5L83

Table 7 provides the specifications for the HVDC transmission bipole options that can meet the required ILM transfer capability increases to 6750 MW and 7120 MW. For the 7120 MW limit, 250 MVAr shunt capacitor is placed at NIC 500 kV bus and 220 MVAr shunt capacitors are added to MDN 230 kV bus. It should be noted that the amounts of reactive power required to compensate each converter do not contribute to the shunt capacitors needed for the ac system.

The 1800 and 2000 MW HVDC bipole options of Table 7 could be made more economic at a lower dc voltage of 400 to 450 kV. However, we adopted for this exercise the 500 kV-based design that was developed for the 2100 MW assessment. If there is further interest in HVDC options a lower voltage should be considered.

Conversion of 5L81 and/or 5L82

5L81 and 5L82 can provide 2,152 MW and 2,264 MW ratings when converted to ±500 kV bipoles as demonstrated in earlier sections of this report. It is also clear from that work that these ratings will not provide the desired 7120 MW ILM capability.

Tripole conversion of 5L81 and 5L82 with a single rating of 2,450 MW for each transmission line would meet the 7120 MW ILM capability as well as the 6750 MW continuous thermal rating. Details of the analysis and of the estimated thermal capabilities are presented in Appendix D.

Table 7: Planning-Level Specifications and Capabilities for 5L83 HVDC Designs to Meet Specified ILM Continuous N-1 and Overload Capabilities under a 470 MVAR Shunt Capacitor Limitation

Comparison Item	Bipole for 6750 MW ILM Continuous Transfer Capability	Bipole for 7120 MW ILM Voltage Stability Limit
Voltage	+/- 500 kV	+/- 500 kV
Conductors	Four-conductor bundle (337.9 mm^2)	Four-conductor bundle (337.9 mm^2)
Conductor Spacing	460 mm	Same as existing ac (460 mm)
ROW Width	Same as existing AC	Same as existing ac
Line Configuration	See Figure 2 below	Same as existing ac
Line Thermal Rating (Limited by converters; normal rating shown; continuous overload 10% higher; sending end power levels shown)	2014: 1800 MW 2020: 1800 MW 2026: 1800 MW 2032: 1800 MW	2014: 2000 MW 2020: 2000 MW 2026: 2000 MW 2032: 2000 MW
ILM Transfer Capability	6,750 MW	7,120 MW
Incremental ILM Transfer Capability Increase	1,750 MW	1,320 MW
Reliability Adequacy (N-2)	Yes	Yes
Converter Losses	0.35% of power flow (variable) 0.35% of converter rating (fixed)	0.035% of power flow (variable) 0.035% of converter rating (fixed)
HVDC line losses at rated load	73 MW (Figure E-1 Appendix E	80 MW Appendix E
Short-circuit Adequacy at NIC	Yes	Yes
Short-circuit Adequacy at ING	Yes	Yes
Reactive Power Equipment for each converter plus additional ac system reactive power requirement	700 MVAr of filters and 340 MVAr of switched capacitor banks at each converter. 360 MVAR (total) at MDN/NIC/KLY	800 MVAr of filters and 360 MVAr of switched capacitor banks at each converter. 370 MVAR (total) at MDN/NIC/KLY
Substation space required at NIC	Yes see Figure H-1 in Appendix H	Yes see Figure H-1 in Appendix H
Substation space required at ING	Yes see Figure H-3 in Appendix H	Yes see Figure H-3 in Appendix H
Availability of Power Flow Control & Stability	Yes	Yes

Table 8 shows parameters for converting 5L82 and 5L81 to tripole. These cases are based on the same conversion limits identified for the 2100 MW expansion scenario and can meet the 7120 MW requirement as well as the lesser 6750 continuous thermal capability.

Table 8: Planning-Level Specifications and Capabilities for 5L81 and 5L82 Tripole Conversion Designs to Increase ILM Transfer Capability under a 470-MVAR Shunt Capacitor Limitation.

Comparison Item	5L82Tripole	5L81 Tripole
Voltage	+./- 430 kV; see text below	+/- 430 kV; see text below
Line Thermal Rating (limited by converters, normal summer rating, continuous overload rating 10% higher)	2014: 2450 MW	2014: 2450 MW
ILM Ultimate Transfer Capability (N-1) (see discussion in the text below)	7120 MW	7120 MW
Reliability Adequacy	No N-1 overload No N-2 with RAS	No N-1 overload No N-2 with RAS
Total Converter Losses (0.35% of continuous loading one end for variable, 0.35% of rating for fixed losses)	35 MW at 2,450 MW	35 MW at 2,450 MW
Line Losses	≈118 (Appendix E, Figure E-1)	≈118 (Appendix E, Figure E-1)
Contingency based Short-circuit Adequacy	17,300 MVA at NIC 12,400 MVA at MDN	17,300 MVA at NIC 16,500 MVA at ING
Reactive Power Equipment Requirement at each converter station	1100 MVAr of filters, 320 MVAR of MSC	1100 MVAr of filters, 320 MVAR of MSC
Substation space required at NIC or MDN	Problematic (see Figure H-1 in Appendix H)	Problematic (see Figure H-1 in Appendix H)
Substation space required at MDN or ING	Problematic (see Figure H-2 in Appendix H)	Adequate (see Figure H-3 in Appendix H)
Power Flow Control capability	Yes	Yes
Staging Options	No	No

With the lower level ILM thermal transfer capabilities of 6750 MW and 7120 MW, it is not possible to significantly stage the conversion of 5L81 and 5L82 to tripole. These lines could be converted in a timely fashion with the first tripole starting operation by 2014 on 5L82. The second (5L81) tripole could be completed within a year or two thereafter.

The tripole conversions under consideration for the lower ILM face N-2 conditions similar to those discussed for the 2100 MW expansion scenario. However, the needed runback or unit dropping is less and is on the order of 300 to 400 MW to keep 5L42 loading within its one-hour summer thermal rating of 2,160 MVA.

Reactive Support

The design of an expansion of the ILM to 6,750 MW and 7,120 MW levels has to take into account a voltage stability limit to the existing ILM transmission grid. This constraint is dictated by the requirement to limit additional MSCs to 470 MVAR. To assess the reactive power requirements in the ac system associated with the selected HVDC options, we adopted the 470 MVAR cap on the total amount of additional shunt capacitor compensation that could be acquired as the study's benchmark. As shown in Table 9, the reactive power requirements of the HVDC options described above were then compared to the 470 MVAR limit. The reactive needs of the HVDC terminal equipment were assumed to be fully supplied by filters and capacitor banks associated with the terminals at all dc power levels. This ensured that the indicated reactive power support would be for the ac system only. NIC, MDN and KLY were the only locations where ac system compensation was applied and summed into the values presented in Table 9. Only the contingencies causing the greater reactive power demand are covered in Table 9.

Table 9: Substation Reactive Requirements for Competing ILM Reinforcement Options When ILM Thermal Overload Is Increased to 7,120 MW

	ILM ac Reactive Power Needs Relative to 470 MVAr			
HVDC Option	**NIC**	**KLY**	**MDN**	**Total**
5L83 as an 1,800 MW Bipole	51	-80	-72	-101
5L83 as a 2,000 MW Bipole	131	-42	-200	-111
5L81 and 5L82 each as a 2,450 MW Tripole	327	59	-181	205

The reactive power demands at each of the listed substations in Table 9 vary significantly depending on the proportion of power flow entering the ILM transmission system at KLY and NIC and on the type of contingency applied. Hence to meet a 100% voltage test for all stations more reactive support would be needed. A detailed study is required to determine the minimum reactive power compensation to be installed at each substation.

Table 9 demonstrates that when a new 5L83 transmission line is operated as a bipole transmission circuit whose converters operate at unity power factor, the reactive power that needs to be supplied to the indicated ILM busbars is less than the 470MVAR limit that would be imposed if the new 5L83 line were 500 kV ac. The results displayed in Table 9 also show that the tripole conversion options will require investing in 205 MVAR of additional reactive compensation above and beyond the 470 MVAR limit. Moreover, ensuring 100% voltage at all stations for all contingencies is bound to increase the need for additional reactive power support beyond the indicated 205 MVAR requirement.

Losses

No total ILM system losses have been determined for ILM operation constrained by the 6,750 MW and 7,120 MW capabilities.

Cost

The HVC line that will meet the 6750 MW and 7210 MW values will be rated 2000 MW. This is 200 MW less than the 2200 MW rating required for the 2100 MW ILM expansion. The cost would thus be approximately $344 million in 2007 dollars (i.e., 91% of the $378.5 million for the larger line)[7]. Staging should provide some reduction in the cost.

Findings

DCI analyses of the potential use of HDC technology to provide a lesser ILM incremental capability increase due to reactive supply economics indicate:

- Constructing a new 500 kV bipole dc line in place of the contemplated 5L83 project using the same ROW represents a conventional HVDC technology alternative that could meet the requirements specified by BCTC.
- Staging of a new 500 kV line could involve construction of a dc-insulated three-phase ac line that would be converted to bipole HVDC later on. Likewise, bipole converter capacity could be staged.
- The combined cost of substation equipment and line costs will be higher for a dc line than the 5L83 EHV AC series compensated benchmark circuit [8]
- Assessing of the economic impacts of loss differences between the ac and the dc versions of 5L83 will not alter the cost gap between the ac and dc alternatives; and
- Converting existing ac circuits into HVDC could meet thermal requirements if tripole technology is applied, but would not meet the ILM reinforcement constraint on reactive power requirements.

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[7] Note that the total HVDC cost is in addition to the benchmark 5L83 EHV AC series compensated circuit cost.

[8] This conclusion is based on the fact that with ac line costs being about the same as dc line costs for the same voltage (e.g. 500 kV), then the larger costs for the dc transmission option result from the much higher costs for a dc converter compared with the ac termination as evident in Table 6. The question may then be asked, why consider dc transmission as an option if it is going to so much more costly? A general answer is that a single circuit 500 kV dc line for the same cost as a dc line, has the potential of transmitting up to 3,600 MW, particularly over long distances. Achieving this power level with an ac circuit will raise the costs of the ac option, perhaps requiring a second circuit thus offsetting the cost of the dc converter station. At the 2100 MW considered in Table 6, a single circuit ac transmission line is far more economical than a 500 kV dc line of the same rating and length. However, the dc option if applied could be upgraded to a higher rating at some time in the future without the need to build another transmission circuit providing it could be reliably accommodated by the power network.

8. Summary

Introduction

This summary covers first the work performed to evaluate HVDC options that can provide 2100 MW of ILM thermal overload capability expansion. An additional task to define HVDC options to meet a reduced transfer capability expansion due to reactive power limitations is also provided under a single heading at the end of this section.

Investigated HVDC Technologies

Two converter arrangements were considered for each HVDC option: a bipole and a tripole design. The bipole connection of HVDC converter-bridges is the accepted industry standard and is the primary arrangement DCI assumed applicable. The tripole configuration is a new converter arrangement that relies on dc current modulation to fully utilize the thermal capacity of all three conductor bundles of a converted ac line. DCI has examined the applicability of this innovation because of its capability to maximize the transfer capability gains from converting ac lines. However, since tripole technology has not been applied in any actual installation, BCTC may not consider it to be a viable option at this time.

Voltage Sourced Converter technology was not considered applicable as an HVDC alternative for the ILM. VSCs for overhead applications incur significant costs when required to provide protection capability during dc line faults. At present, VSC technology applications are limited to back-to-back and dc cable installations.

Advantages and Limitations of HVDC Transmission

Operating HVDC circuits in parallel with ac lines brings about a number of advantages and disadvantages relative to ac-only systems, including:

1. Long HVDC lines have lower losses than equivalent ac lines in general;
2. HVDC provides significantly higher ROW power density and hence requires less ROW for equivalent power transfer;
3. Converters and associated equipment are expensive and require relatively large station footprints;
4. HVDC requires high levels of MVAr support (about 50 percent of the rated MW transfer capability);
5. HVDC does not provide synchronizing power following power system faults without special controls to mimic an ac circuit response;

6. HVDC bipole is in effect two circuits (much like a double-circuit ac transmission line) and therefore provides 50 percent of the line thermal capability upon loss of one conductor bundle (an earth return is required to make use of this capability and may be limited to one hour of use);
7. HVDC does not increase short circuit levels thereby potentially lowering the duty and cost of adjacent switching equipment;
8. Reclosing following a fault (the equivalent of single pole reclosing for ac lines) does not incur the large fault currents of ac line faults and restoration is faster;
9. HVDC provides inherent power flow adjustment, allowing either manual or automatic setting of power flows to address contingencies and reduce losses;
10. Where the short-circuit level is low, dynamic reactive equipment may be needed to ensure HVDC converter commutation; and
11. Life cycle costs of HVDC should account for replacement expenses at the end of useful equipment life; however, given that the economic life of HVDC facilities is 40-50 years, the discounted end costs may not be significant.

On balance, and with reference to the above first five attributes, an HVDC line within a synchronous ac network is generally preferable to an equivalent ac circuit if the combination of loss savings and ROW space reduction benefits are sufficient to overcome the HVDC converter and additional MVAr supply (filter) costs. As directed by BCTC, ROW and station space costs or savings were not addressed in this study. Any special HVDC control requirements are not considered a significant cost item for the purposes of this study. This leaves HVDC converters and MVAr supply costs and loss reduction as the primary economic factors to be considered.

Identified HVDC Options Compared on a Thermal Overload Basis:

DCI evaluated several HVDC transmission alternatives to EHV AC including:

1. A two-conductor HVDC line in place of 5L83 utilizing the same corridor;
2. A three-conductor 5L83 without series capacitors and with staged conversion to HVDC;
3. Conversion of 5L81 or 5L82 to HVDC, and
4. Conversion of both 5L81 and 5L82 to HVDC.

In addition to the above, a cursory investigation was made of the potential for conversion of 5L40, 5L41 and 5L42 and the 230 kV KLY ILM circuits. Because the 500 kV circuits would involve conversion costs roughly similar to those for 5L81 and 5L82 while likely providing lesser contribution to thermal transfer capability, no explicit analysis was done for these options. Further, no conversion of 230 kV circuits was found to provide the incremental total transfer capability that could match 5L83 as required by BCTC.

Comparison of HVDC with 5L83 on a Thermal Overload Basis

An HVDC bipole line and a staged 5L83 conversion (starting with the bench mark 5L83 energized initially as an ac line without series capacitors and insulated for dc and later converted into bipole) represent the two HVDC alternatives that could match the capabilities of 5L83 with its full compliment of the series capacitors. Conversion of 5L81 and 5L82 to bipole HVDC was found to be less effective. The inability to utilize one conductor bundle during the bipole operation of 5L83 and the existing 5L81 and 5L82 ac lines when converted to bipole HVDC, severely limits the HVDC contribution to ILM thermal overload capability. Tripole overcomes this barrier and does provide the required 2100 MW of incremental thermal overload capability from the conversion of either 5L81 or 5L82. However, this option has contingency limitations as do the 5L81 and 5L82 bipole conversions. Moreover, as stated above since tripole is not a proven technology it is not presented here as a contender at this time. The HVDC line in place of 5L83 and the staged 5L83 conversion alternatives were found to be the most effective HVDC options.

For the purposes of our analysis, and since BCTC specified the study to be “a planning level estimate”, the same 5L83 conductor size was assumed for both of the identified HVDC alternatives (rather than designing an optimal conductor size for each option).

Reactive Power Requirements for Options Comparable on a Thermal Overload Basis

As indicated by Table S-1, reactive power requirements were found to increase for MDN, ING, NIC and KLY. The observed increases reflect the expected rise in ILM power flow under the various studied options. It should be noted that the values shown in Table S-1 do not include reactive power that will be required for the collecting systems north and east of the ILM interface, nor does it include the additional MVArs that the Lower Mainland system will need to receive the power. These requirements will not change measurably among the ILM upgrade options and thus are not included. Estimates of the reactive power requirements are intended to maintain ac voltage above 100% of normal operating voltage at the identified 500 kV substations and below 1.05 per unit for selected contingencies. The actual determination of reactive power needs and how they would be met involves a very detailed study that is beyond the scope of this project.

Table S-1: Substation Reactive Power Requirements for the Competing ILM Reinforcement Scenarios

Alternatives	2014 (MVAr)					2026 (MVAr)				
	MDN	ING	NIC	KLY	Total	MDN	ING	NIC	KLY	Total
Base Case 5L83 AC 50% series compensated	520	350	130	-200	800	900	750	380	200	2230
HVDC Alternative #1 - HVDC line on 5L83 corridor	380	230	400	60	1070	770	780	630	130	2310
HVDC Alternative #2- Stage 1 operating 5L83 ac without series capacitors	520	350	130	200	1200					
HVDC Alternative #2 - Stage 2 conversion to bipole dc						770	780	630	130	2310

System Reactive Power Requirements for a Limited ILM Transfer Capability Expansion

Table S-2 presents the reactive power requirements to be added at NIC, KLY and MDN for the reduced power transfer requirement of 7120 MW associated with the 470 MVAR reactive power limit.

Table S-2: Reactive Needs for ILM Expansion Options for 7120 MW ILM Voltage Stability Capability

	ILM ac Reactive Power Needs Relative to 470 MVAr			
HVDC Option	NIC	KLY	MDN	Total
5L83 as an 1,800 MW Bipole	51	-80	-72	-101
5L83 as a 2,000 MW Bipole	131	-42	-200	-111
5L81 and 5L82 each as 2,450 MW Tripole	327	59	-181	205

System Losses

Table S-3 provides estimates of system losses for 2014 and 2026 peak ILM-flows for 5L83 and the two HVDC options that could match it for the 2100 MW thermal overload capability benchmark. The displayed values encompass the entire BCTC system including the proposed ILM upgrades. For the dc options, each converter station was assumed to have 0.35 percent in fixed losses and 0.35 percent of variable losses. Line losses were additional and are included.

Table S-3: Estimates of Peak-Flow System Losses for Competing 2100 MW ILM Reinforcement Options

ILM Option	2014 Peak Losses (MW)	2026 Peak Losses (MW)	2014 Difference in Losses c/f Base Case (MW)	2026 Difference in Losses c/f Base Case (MW)
Base Case 5L83 AC	767	1001	0	0
Alternative #1 - HVDC line on 5L83 corridor	770	1003	3	2
Alternative #2 - Stage 1 operating 5L83 ac without series capacitors	777	-	10	-
Alternative #2 - Stage 2 conversion to bipole dc	-	994	-	-7

Costs of Options Comparable on a Thermal Overload Basis

Table S-4 summarizes DCI's estimates of the costs of undertaking the ILM thermal reinforcement alternatives under consideration. The displayed values do not include interest during construction, the purchaser's engineering and administration costs, contingencies or additional reactive power compensation costs. BCTC may wish to include these costs in their final analysis if other cost differences are not conclusive. The capital costs of the alternatives under study have been derived on the basis of published information from suppliers and CIGRE[9]. They include the contract price of the supplier for turnkey installation in 2007, site preparation expenses, project supplier's engineering and administration fees, and the costs of spares and ground electrodes. Transmission line construction costs are not included. The exhibited estimates are budgetary within an accuracy of -10 and +20 percent.

[9] CIGRE Brochure WG14.20: "Economic Assessment of HVDC Links," 2001

Table S-4: Estimates of the Capital Costs in 2007 Dollars of the Competing ILM Reinforcement Options

ILM Option	NIC Converter ($\$M_{2007}$)	MDN Converter ($\$M_{2007}$)	Total ($\$M_{2007}$)
Base case 5L83 EHV AC (2100 MW)[10]	0	**0**	**0**
Alternative #1- HVDC line on 5L83 corridor (2200 MW)	182.7	195.8	378.5
Alternative #2 - Stage 1 operating 5L83 ac without series capacitors (1400 MW)	0	0	-20
Alternative #2- Stage 2 conversion to bipole (2100 MW)	182.7	195.8	378.5

Findings for Thermally Comparable Options

DCI analyses of the options for a 2100 MW of incremental thermal overload capability increase indicate:

- Constructing a new 500 kV dc line in place of the contemplated 5L83 project using the same ROW represents a conventional HVDC technology alternative that could meet the requirements specified by BCTC;
- Constructing a 500 kV conventional ac circuit without series capacitors followed later by conversion to bipole dc also appears to meet the specified BCTC requirements;
- HVDC alternatives to 5L83 are significantly more costly than an ac 5L83;
- Assessing of the economic impacts of loss differences between the ac and the dc versions of 5L83 will not alter the cost gap between the ac and dc alternatives; and
- Converting existing ac circuits into HVDC will not meet the ILM reinforcement requirements as stated by BCTC.

The above findings are limited to the comparison of 5L83 and credible HVDC options that might compete with 5L83 in the 2014 to 2026 time frame as examined in the documented analysis. A longer-term perspective might show different conclusions. That is, comparing HVDC and ac options that might be required to expand the ILM beyond 2026, perhaps through 2036 might give rise to other conclusions. For instance, if some future generation development were to require transmission upgrades to the north or east of KLY or NIC, HVDC might serve that generation as well as cover needs on the ILM. However, in our judgment, the present worth of any incremental advantages that might be found would be small and unlikely to change BCTC

[10] Note that with a zero cost shown for 5L83 EHV AC, the line costs for the HVDC in this table do not include the HVDC line costs.

conclusions based on analysis of the 2014-2026 time frame. Additionally, if tripole technology is accepted and demonstrated, BCTC will have some options available to expand the ILM transfer capability by converting the 5L83 already in place should expansion is deemed attractive beyond 2026.

Findings for Options Comparable on the Basis of Reactive Limitations

The analysis in Section 7 develops HVDC options that are comparable with 5L83 if 5L83 is limited to adding an incremental ILM voltage stability limit of only 1320 MW and an incremental thermal N-1 capability of 1750 MW. The findings of that analysis are:

- Constructing a new 500 kV bipole dc line in place of the contemplated 5L83 project using the same ROW represents a conventional HVDC technology alternative that could meet the requirements specified by BCTC;
- Staging of a new 500 kV line could involve construction of a dc-insulated three-phase line with later conversion to bipole. Likewise, bipole converter capacity could be staged;
- The combined cost of substation equipment and lines will be higher for a dc option than for 5L83;
- Assessing the economic impacts of loss differences between the ac and the dc versions of 5L83 will not alter the cost gap between the ac and dc alternatives; and
- Converting existing ac circuits into conventional bipole HVDC could meet thermal requirements if tripole technology is applied, but would not meet the ILM reinforcement constraint based on limited reactive power support.

Appendix A – Essentials of Conventional HVDC Technology

In its simplest form, an HVDC line consists of two converters at either end of a conductor. One is a rectifier converting ac power to dc and the other is an inverter that can convert dc back to ac. The conductor may be a cable of overhead line as shown in Figure A-1 (a). There is a second conductor in the form of ground electrodes and the earth between them. While this monopole design has been used where the earth can be used as one of the conductors, it is rare because the earth currents can cause corrosion of metal objects (pipelines) buried in the earth.

The more popular arrangement uses two converters at each end, one forming a positive pole and the other a negative pole. The result is two currents that balance and eliminate current in the ground electrodes and earth path. In this arrangement the earth path is used only during outage of one of the insulated conductor poles. This is shown in Figure A-1 (b).

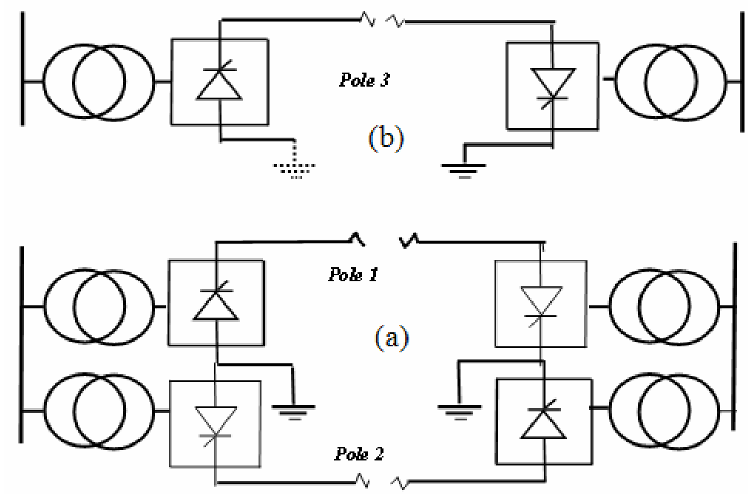

Figure A-1: Monopole and bipole HVDC transmission configurations

Both converters can be operated as either a rectifier or an inverter, thus allowing power to flow in either direction.

Under normal operating conditions the voltage imposed on the transmission line by the converters is held constant by converter controls that do so to hold current constant and thereby constant power flow as well. The power flow can be adjusted by changing the voltage setting at the rectifier or the converter. This can be done quickly though it is usually done by operators at a remote location. Controls can also be put in place to automatically respond to changing conditions in the adjacent ac

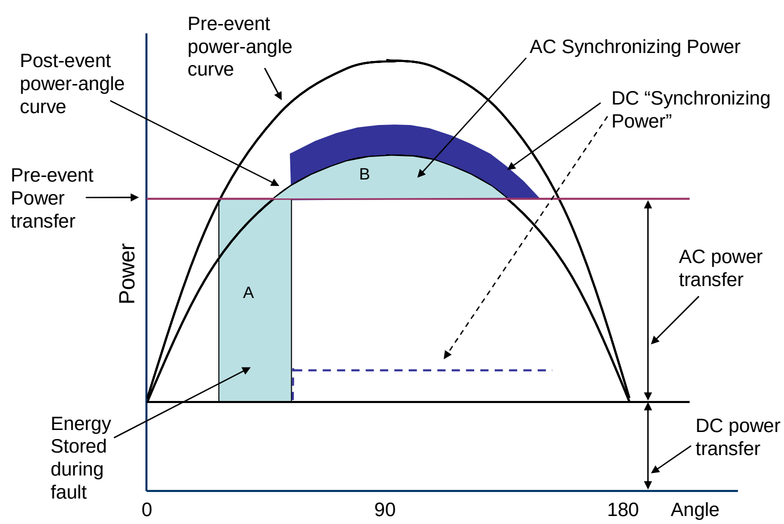

Figure A-2: Two machine equal area criterion system, perhaps reducing dc power flow when voltage falls in the ac system or increasing dc power flow when an ac system outage occurs.

When the bipole dc line is part of an ac system, it may need to help ensure stability of the ac system. It can do this with controls that adjust power so that the dc line behaves much like an ac line when a power swing occurs in the system. Figure A-2 shows the change in dc power that can be provided for this purpose. Figure A-2 is a two-machine or two-system power-angle curve familiar to ac system planners. Under the equal area criteria, the system is stable if area B exceeds area A. Area A represents the energy stored in sending end generators during a fault and area B represents the synchronizing power that extracts that energy and brings the sending end generators back to synchronous speed. Area B can be increased by stepping power up on the dc line during or following the fault thus mimicking ac synchronizing power and increasing total synchronizing power. Unlike ac synchronizing power that builds only as the system angle increases, HVDC synchronizing power can be applied quickly and can thus be very effective.

An ac circuit converted to HVDC will not reduce ROW it needs. A new transmission line built to operate tripole may require somewhat less ROW due to less difficult HVDC fields. A line constructed to operate as a tripole can be built in a delta configuration to reduce ROW requirements. There is the capability for higher power density with an HVDC line compared to an ac line of similar rated voltage. For an example, a 500 kV HVDC bipolar line may accommodate 3000 MW or greater power transfer capability. A 500 kV ac single circuit line with series compensation and depending on its length, may have a power transfer capability of 1500 MW to 2200 MW, substantially less than the HVDC circuit

Appendix B – Early BCTC Experience with HVDC

BCTC has extensive experience with HVDC. A monopole HVDC system was installed in 1969 (Pole 1) and a second opposite polarity monopole system was installed in 1976 (Pole 2). This HVDC system is largely cable and runs between ARN and VIT. This system essentially parallels the 138 kV AC system. The HVDC system consists of two single-pole subsystems (Pole 1 & Pole 2), each of which can be independently operated with earth return. Each pole subsystem contains large converter stations located at ARN and VIT, HVDC submarine cables and overhead lines. The connection to Vancouver Island through the HVDC system is non-synchronous.

The original design rating of the Pole 1 mercury arc converter subsystem was 312 MW, and the Pole 2 thyristor valve converter subsystem was rated 370 MW and can be overloaded to 476 MW under low ambient temperature. Both HVDC converter systems were designed and build while HVDC technology was developing fairly rapidly. As such they are technically obsolete. Additionally, they are no longer supported by the original manufacturer making upkeep and repair costly. They are among the last few systems of their kind in operation anywhere in the world.

Pole 1 is normally operated in standby and no longer has any dependable capacity. The dependable capacity of Pole 2 has been de-rated to 240 MW until 2007, and it will be rated at zero for planning purposes for the winter of 2007/2008. This means that the HVDC system can no longer be relied upon to provide any firm capacity to Vancouver Island after 2007. Limited investments have been made in the HVDC system to extend its life until replacement capacity can be put in service. The HVDC equipment and cables will still be available for emergency operation beyond 2008 as long as it is found economically feasible to maintain the system in an operable condition.

While this HVDC equipment was built during the early years when HVDC technology was progressing rapidly, it has nonetheless provided a useful life of 30 to 35 years. By about 1980, HVDC technology had largely matured and newer systems are usually assumed to have longer life, on the order of 40 to 60 years with only modest upgrade and renewal expenditures during that period.

Appendix C – Essentials of Tripole Technology

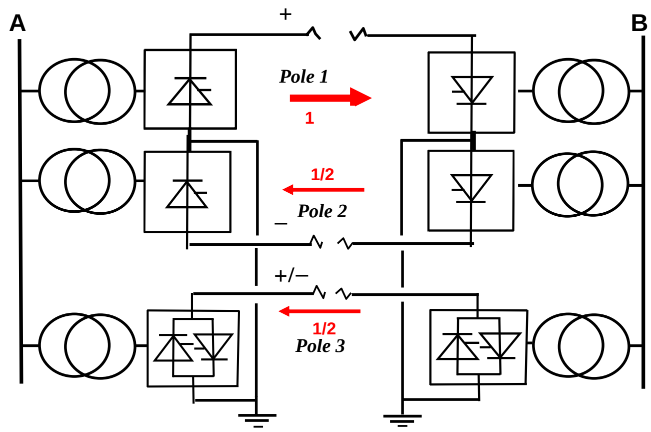

Figure C-1: Tripole configuration

A tripole HVDC line differs from a bipole HVDC line in three significant respects. It utilizes a third conductor, it adds a third converter, one able to operate with either polarity, and controls to manage conductor loading. The basic structure is shown in Figure C-1. The normal operating mode is shown in Figure C-2. Two conductors alternate between an overload and underload condition averaging, from a thermal standpoint, the conductor thermal rating. The third pole carries fully conductor current continuously, but reversing at a several minute interval.

Tripole HVDC is ideally suited for conversion of existing ac transmission lines to HVDC. It can make use of all three phase conductors, substantially increasing the line capability.

The optimal line design for a tripole HVDC line is a delta configuration. This arrangement reduces conductor electric field gradient compared to a typical flat ac line design. This configuration is taller than and equivalent ac line, but does require only about 70% of the ROW of an ac line.

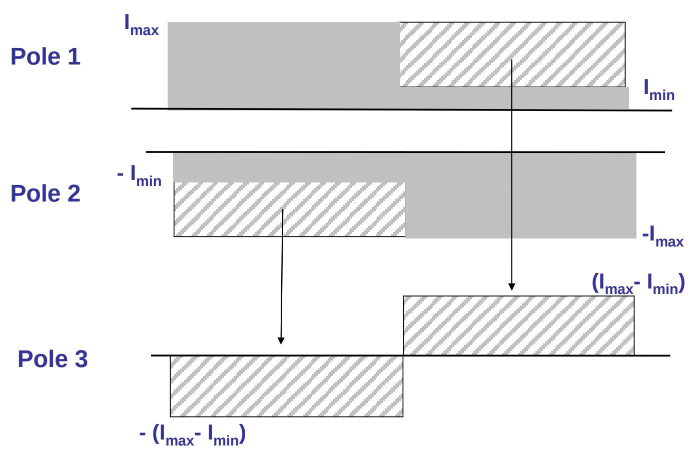

Figure C-2: Normal operating mode for tripole

An important issue with the tripole arrangement is the application of reliability criteria. NERC and all regions treat a bipole HVDC line as two circuits on a single tower if a ground return is provided and system adjustment can accommodate any time limitation on use of the ground return path. Loss of one of the two poles is considered to be an N-1 event under Category B of the NERC criteria. Tripole's advantage will only be fully realized if it receives the same treatment. This treatment has not yet been established and is likely to be established only when the first tripole line is proposed. We see no reason why such treatment will not be acceptable. Loss of one pole of a tripole line leaves two poles that can be operated in bipole mode. One advantage of the tripole is that it does not need to make use of a ground return path following an N-1 pole loss and thus requires much less system adjustment to accommodate the next N-1 event. If a ground return path is available, a tripole line can lose two poles and continue operating at a lower loading.

As with bipole HVDC, conversion from ac to HVDC tripole can be done with virtually no interruption of transmission line operation. The problem of reduced reliability during conversion is thus avoided.

Tripole HVDC shares the same controllability and dynamic capabilities as outlined in Appendix C for bipole lines, though the short-time overload capability to address synchronizing power needs is about twice that of a bipole configuration.

Generally, a tripole line will have the following advantages over a bipole line using the same three-conductor transmission line:

- 37% more MW Capability for the same dc voltage
- 9% Higher 30 Minute overload capability
- Twice the 1-second synchronizing power potential
- 84% redundancy compared to 57% for a bipole
- ~ 15% to 20% higher cost/kW

It will have the disadvantage of somewhat lower operating voltage than a bipole where conductor gradient is the limiting factor in post conversion dc voltage.

While loss of one pole of a bipole line drops power transfer 43% when 15% overload capability is available, that same overload capability results in only a 16% drop in power transfer when one pole of a tripole line is lost. The N-1 impact of a pole outage on a tripole line is thus significantly less than is the case for a bipole line. Additionally, loss of one pole does not require ground return operation in a tripole line as it does in a bipole line.

Appendix D – Thermal Capability of Converted Lines

Introduction

The ampere limit of an ac line, converted to dc line will usually be within 1% of the *rms* ac current limit. But conversion will increase MW capability by allowing the line to operate at what would correspond to ac *crest* voltage rather than ac *rms* voltage. Furthermore conversion will often allow a dc voltage above line-to-ground crest ac. In the bipole case this advantage is largely offset by the fact that only two of three phase positions are active in the transmission of power. In the tripole case, all phase positions are used. Because of the importance of dc voltage to the rating of all dc options, allowable dc voltage was the focus of investigation in considering conversion of BCTC 230 kV, 360 kV and 500 kV circuits to DC, emphasis being on the latter.

Line Configuration Assumptions

500 kV: The majority of both circuits 5L81 and 5L82 consist of a four conductor 316 mm^2 conductor bundle. Phase to-phase spacing and average conductor height vary for different line sections. Table 1 shows the assumptions made to represent both, erring on the pessimistic side of close spacing and low average height. Both circuits involve very small segments of 2 bundle configuration near terminals. These segments were not considered limiting.

360 kV: This circuit, characteristics of which are also shown in table D-1 is essentially the same conductor configuration as 2L1 and 2L2 230 kV lines, though it is now operating at 360 kV. Since its capability has already been increased by ac voltage up-rating, it's not surprising that the relative boost in capacity achieved by dc conversion is less than with 230 kV circuits which have not.

230 kV: Circuit 2L1 is mainly comprised of a Condor (795 mm2) conductor except for very short distances near the terminals and is characterized as such in table D-1. Circuit 2L2 is comprised of 2 Drake (403 mm2) conductors except for short terminal sections. It is so represented in table D-1.

D-1 Transmission Line Dimensions

		Conductor		Configuration	
Circuit(s)	kV	mm^2	d (cm)	H (m)	P-P (m)
5L81,82	**500**	4X316	2.41	22	11.8
3L2	**360**	2X403	2.814	16.8	9.14
2L1	**230**	1X795	2.776	10.7	7.92
2L2	**230**	2X403	2.814	16.8	9.14

Allowable dc voltage on converted circuits

The dc voltage sustainable by an ac line will be set by the lower of several limits; (a) maximum conductor gradient (b) earth surface gradient, (c) safety code dictated line-to-ground clearance limits, (d) Insulation limits, and (e) air gap clearances at the tower. For estimating purposes, conductor surface gradient was taken as the first criterion for estimating the dc voltage potential of BCTC line configurations. A conductor gradient criterion of 26 kV/cm was assumed. This criterion is based on the fact that higher dc gradients on actual operating lines are suspected to be associated with occasional unexplained flashovers of HVDC lines.

Conductor surface gradient calculations were made for 230 kV, 360 kV and 500 kV configurations. In each case the dc voltage was adjusted to produce the criterion surface gradient of 26 kV/cm. The result suggests somewhat higher voltage for the bipole configuration than the tripole inasmuch as the tripole will have an outer pole at one polarity with two remaining poles at opposing polarity while the bipole has opposing voltages only on the outer phase positions. If the bipole is to be operated so as to allow substitution of the ground return pole position for either of the poles in the event of a forced or maintenance outage of one of the latter, the allowable dc voltage would be within 1% or 2% of the tripole limit. If a bipole is operated with split return to minimize losses, the gradient-limited dc voltage would be identical to the tripole limit.

The results of maximum gradient calculations showed that, for the gradient criterion chose, pole-to-ground voltages of 486 kV for the bipole dc option and 418 for the tripole option could be sustained. This assumes the bipole would use only the two outer phase positions as noted above. The above voltage values were rounded up slightly to 500 kV for the bipole and 430 kV for the tripole based on the pessimistic line dimension combinations on which calculations were based, i.e. the combination of adverse phase separation and height values.

The tripole solution, at 430 kV, produced an unacceptable gradient on the shield wires, implying that for the short distance this shield wire extends from the stations, shield wires would have to be either repositioned or replaced.

Tower insulation and midspan clearance limitations constitute another potential limit to dc voltage rating of 5L81 and 5L82. The existing structures now use 23 insulators per phase position. If each were replaced by 23 HVDC Fog-type units, having higher creepage but the same length, prudent practice in a zone of very low pollution would suggest a voltage limitation of approximately 17.5 kV per insulator or, for 23 insulators, approximately 400 kV dc.[11, 2] However the lower surge levels associated with dc would allow addition of insulators and proportionate increase in dc voltage until limits on the electrical clearance at midspan are reached. While no specific calculations were made for the 5L81 and 5L82 case, the increase in voltage achievable by adding insulators on this basis is generally in the order of 25%, thus suggesting a maximum dc voltage, from the standpoint of this criterion, of 1.25 x 400 = 500 kV. The prospect of that great an extension of insulator length would have to be examined with respect to the reduction in clearance from the conductor to the tower walls during extreme wind swing. However since that clearance is based on switching surges and those surges are substantially less for dc than ac, it is likely that air gap clearance would not be limiting for increases in insulator

[11] IEC 60815, "Guide for the selection of insulators in respect of polluted conditions, First edition, 1986
[2] IEC TS 60071-5 "Guide for the selection of insulators in respect of polluted conditions

length of that order. Thus insulation does not appear to limit the voltages that would be otherwise acceptable from a conductor gradient standpoint.

Current Ratings

Table D-2 replicates the ILM-HVDC Project: Transmission Line Thermal Rating Table (from the file LineRating.xls), representing both summer and winter continuous and emergency ratings. One important exception was taken with respect to current ratings given in that table. That table shows a continuous MVA rating for circuit 3L2 of 1,111 MVA for winter and 632 MVA for summer, both of which can be converted to ampere ratings at that voltage. The same conductor configuration prevails over almost all of circuit 2L2, yet much lower ampere ratings result from converting the MVA ratings in the table to amperes at 230 kV. It is presumed that the disparity is due to 230 kV line terminals sections. On that basis the same ampere ratings are assigned to 2L2 as are given for 3L2.

D-2 Normal and Emergency Circuit Ratings

			Winter				Summer			
			Continuous Rating		Overload Rating (MVA)		Continuous Rating (MVA)		Overload Rating	
LINE	FROM	TO	Series Capacitor Rating	Conductor Rating	Series Capacitor Rating	Conductor Rating	Series Capacitor Rating	Conductor Rating	Series Capacitor Rating	Conductor Rating
2L1	BRT230	CKY230	N/A	352	N/A	352	N/A	201	N/A	201
2L2	BRT230	CKY230	N/A	508	N/A	508	N/A	417	N/A	417
2L9	CKY230	LYN230	N/A	475	N/A	475	N/A	390	N/A	390
2L90	BRT230	KLY230	N/A	355	N/A	355	N/A	203	N/A	203
3L2	ROS360	BRT360	N/A	1111	N/A	1111	N/A	633	N/A	633
5L41	KLY500	CBK500	1645	2875	1892	2875	1645	2165	1892	2165
5L42	CKY500	KLY500	1888	2711	2187	2918	1888	1862	2187	2165
5L44	MDN500	ING500	N/A	3005	N/A	3005	N/A	2165	N/A	2165
5L81	ING500	NIC500	1836	2711	2425	3217	1836	1864	2425	2598
5L82	MDN500	NIC500	1836	2860	2425	3291	1836	1961	2425	2598
5L87	NIC500	KLY500	2078	3710	2598	3710	2078	3066	2598	3066

Power Ratings

Table 3 presents the voltage ratings based on the lower of two criteria; (a) that derived in accordance with the 26 kV/m criterion and (b) estimated insulation capability of the towers. The current ratings from table 1 and the steady-state characteristics of both bipole and tripole HVDC systems, bearing in mind that bipole dc power is simply twice the dc voltage times the dc current or, in megawatts:

$$P_{bipole} = \frac{2.00(kV_{dc-bipole})I}{1000} MW \qquad (1)$$

and tripole dc power, discussed in appendix d is 1.37 times that, or:

$$P_{tripole} = \frac{2.74(kV_{dc-tripole})I}{1000} MW \qquad (2)$$

Normal ratings in table D-3 are shown in black (left column), emergency ratings in red (right column). Those ratings are dependent on the voltage assumption for both bipole and tripole voltages. The voltage ratings for 3L2, 2L1 and 2L2 are based on a conductor gradient criterion of 26 kV/cm and assume no limitations due to insulation at the tower. That assumption should be checked if conversion of these circuits is contemplated inasmuch as it might limit dc voltage to a lower level

Several characteristics of the ratings in table D-3 are particularly germane to load flow and reliability calculations:

The emergency ratings of the tripole assume accommodation of earth return current for the emergency period, i.e. a conventional (unmodulated) bipole and a monopole configuration in parallel, increasing the tripole rating by the ratio 1.5/1.37 = 1.09.

D-3 Estimated dc Ratings of BCTC ac Circuits

									MW Rating									
	DC kV		Current Rating						Bipole				Tripole					
Ckt	Bipole	Tripole	Winter		Summer				Winter		Summer		Winter		Summer			
5L81	500	430	3,130	**3,715**	2,152	**3,000**			3,130	**3,715**	2,152	**3,000**	3,688	**4,792**	2,536	**3,870**		
5L82	500	430	3,303	**3,800**	2,264	**3,000**			3,303	**3,800**	2,264	**3,000**	3,891	**4,902**	2,668	**3,870**		
3L2	308	222	1,782	**1,782**	1,015	**1,015**			1,098	**1,098**	625	**625**	1,084	**1,187**	618	**676**		
2L1	240	207	1,782	**1,782**	1,015	**1,015**			855	**855**	487	**487**	1,011	**1,107**	576	**630**		
2L2	308	222	1,782	**1,782**	1,015	**1,015**			1,098	**1,098**	625	**625**	1,084	**1,187**	618	**676**		

For (n-1) purposes, loss of a pole on the bipole configuration at maximum rating will impose 50% of that rating on the surrounding ac system. If the DC is credited with 15% overload capability, that loss of real power drops to 1-.5x1.15 =0.43. If the tripole circuit drops a pole at maximum load, the power loss is (1.37-1.00)1.37 = 27%. If overload capability is recognized in this case, the loss is (1.37-1.15)/1.36 = 0.16.

Summary

Based on reasonably conservative assumptions, conversion of 5L81 or 5L82 would appear to support voltages in the order of 500 kV for a bipole and 430 kV for a tripole configuration; 1.22 and 1.05 times line-to-ground crest ac voltage respectively. The resulting MW capabilities favor the tripole by about 18% for normal ratings and 30% for overload rating, the latter reflecting the dc circuit's ability to support loss of a parallel ac circuit.

The comparison of the MW transfer rating of 5L81 and 5L82 as ac circuits, constrained by series capacitors and as dc circuits constrained by thermal rating of conductors is shown in table D-4.

D-4 Summary and rating comparison

	Winter		Summer	
	Normal	Emerg.	Normal	Emerg.
MVA	1,836	2,445	1,836	2,445
MW @ pf = 0.9	1,652	2,201	1,652	2,201
Bipole @ 500 kV - MW	3,130	3,715	2,152	3,000
Bipole @ 500 kV - pu	1.9	1.7	1.3	1.4
Tripole @ 430 kV MW	3,891	4,902	2,668	3,870
Tripole @ 430 kV pu	2.4	2.2	1.6	1.8

Appendix E – Losses for New and Converted HVDC Lines

The red curve in Figure E-1 shows losses vs. MW for the 272 KM 500 kV line 5L81 using a 4x316 mm2 conductor configuration and assuming a power factor of 0.9. The curve is solid up to the bundle's summer operating rating of 1,864 amperes and dotted above that rating up to its emergency winter rating. At its summer continuous rating, losses are approximately 92 MW for a presumed power level of 1676 MW (assuming the above power factor): a loss of approximately 5.5%. The dotted black curve in Figure E-1 extends that 5.5% loss rate for reference purposes.

The blue curve in Figure E-1 shows bipole losses vs. MW based on use of two conductors with the third as an earth return. It assumes a bipole voltage of 500 kV. The upper limit shown for the bipole corresponds to winter emergency operating conditions. The dc losses include converter terminal losses at 0.7% of transmitted power for each of two terminals. At a 2,200 MW full overload bipole rating with two active conductors, the total line and station losses are 91 MW as per the blue curve on Figure G-1. The total HVDC line and station losses would reduce to 76 MW with the third conductor operating in parallel with one pole conductor (not shown in Figure G-1). It is possible to parallel the third conductor to an operating pole during bipole operation and use a switching arrangement to bring it into a metallic return configuration and relieve the use of a ground return path for an extended monopole operation.

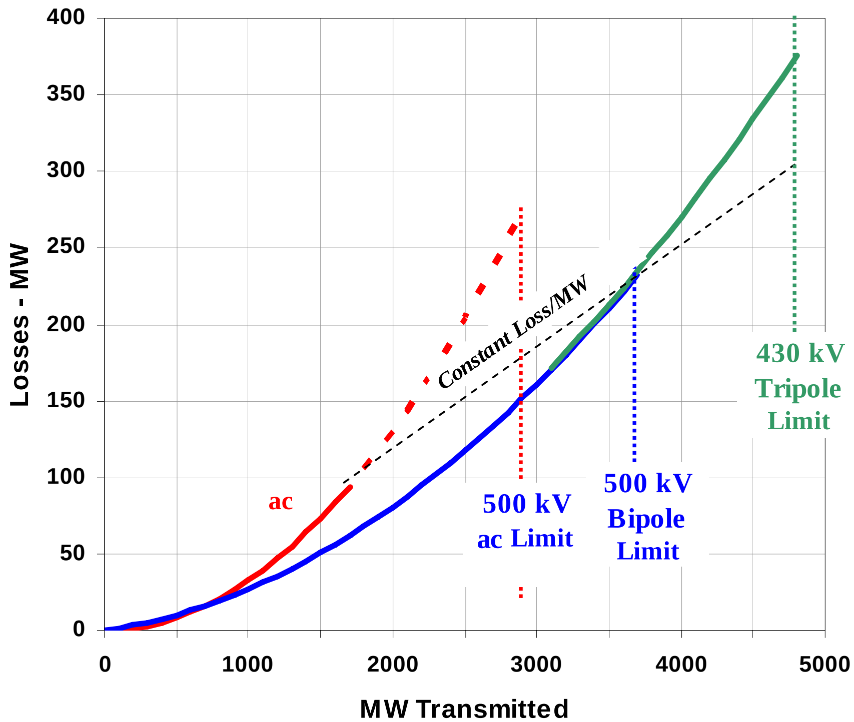

Figure E-1: Loss characteristics of ac and dc configurations for equal MW transmission (pf=0.9)

The green curve in Figure E-1 shows losses for the same line operating with a 430 kV tripole configuration using all three conductors. The tripole advantage in losses per kW is, in this case, offset by the difference in operating voltage. Only at the higher end of the tripole range do losses, as a percent of operating power, exceed the level which characterizes the ac case at its summer continuous rating. The tripole case assumes that over all but the top few percent of the tripole capability range, the line would operate with a modulation ratio of 2, i.e. with current in one pole returning in equal amounts on the other two. Bipole losses could be reduced by operating with two conductors sharing the return current, however that would result in a drop in gradient-limited voltage, negating this advantage in addition to introduction of certain operating disadvantages.

Appendix F – Single Line Diagrams of the Examined Options with Costs

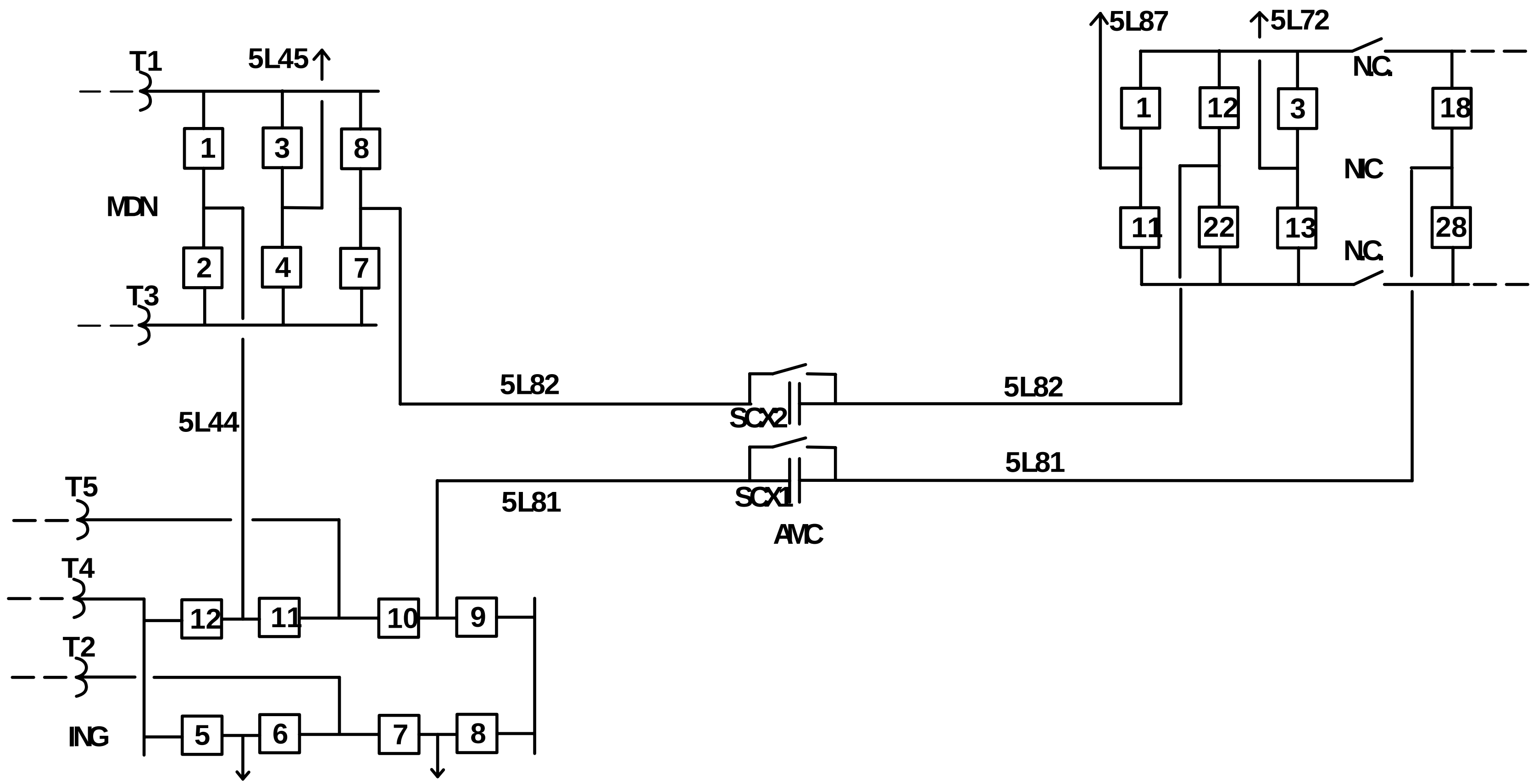

Figure F-1: B CTC System as it is today.

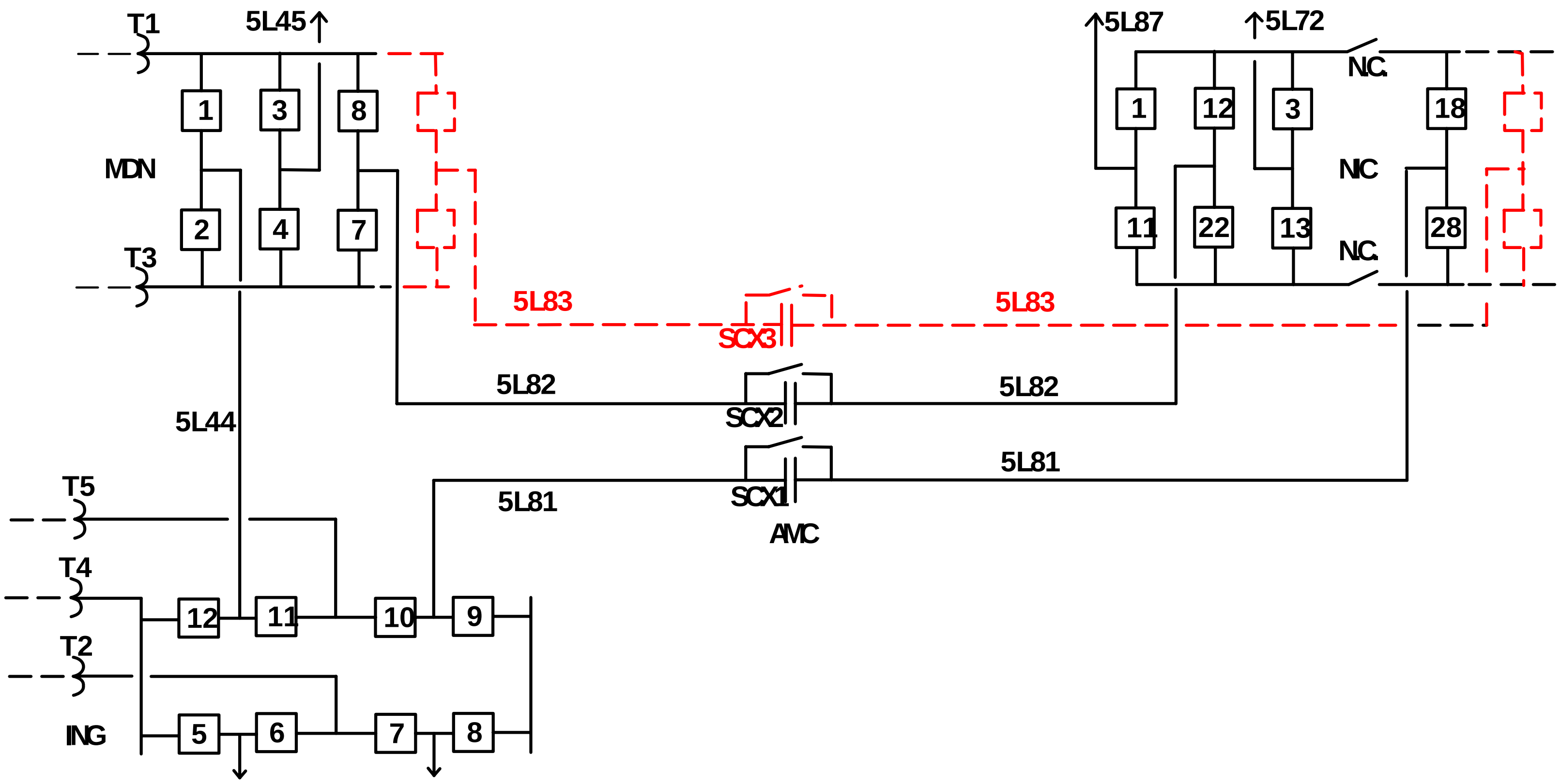

Figure F-2: BCTC system with series compensated ac line 5L83 added.

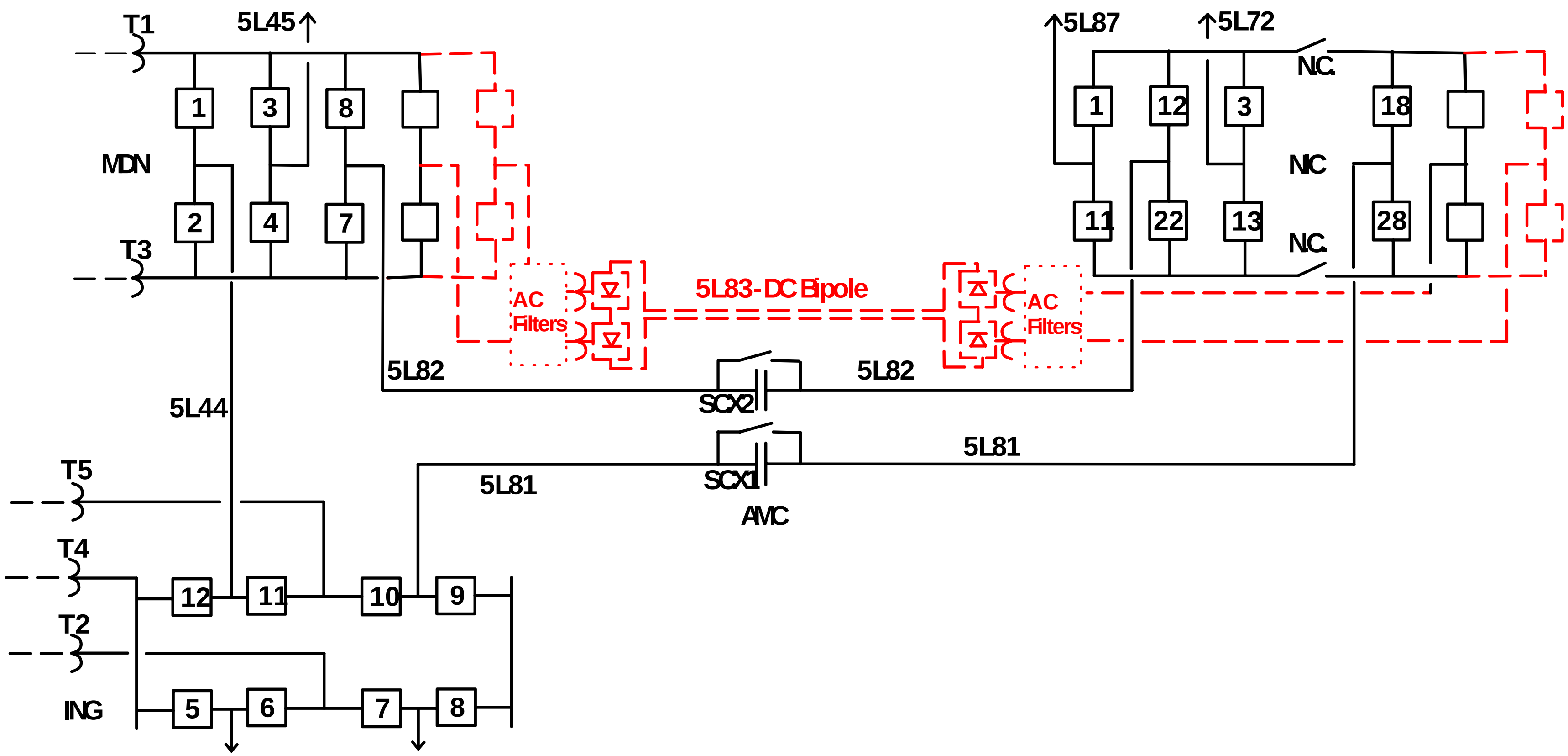

Figure F-3: New Line 5L83 built as a 500 kV dc bipole line.

Stage	MDN DC Converter CDN$M₂₀₀₇	NIC DC Converter CDN$M₂₀₀₇	Total CDN$M₂₀₀₇
1,800 MW Bipole	173.6	161.8	335.5
2,000 MW Bipole	183.0	170.6	353.6
2,200 MW Bipole	195.8	182.7	378.5

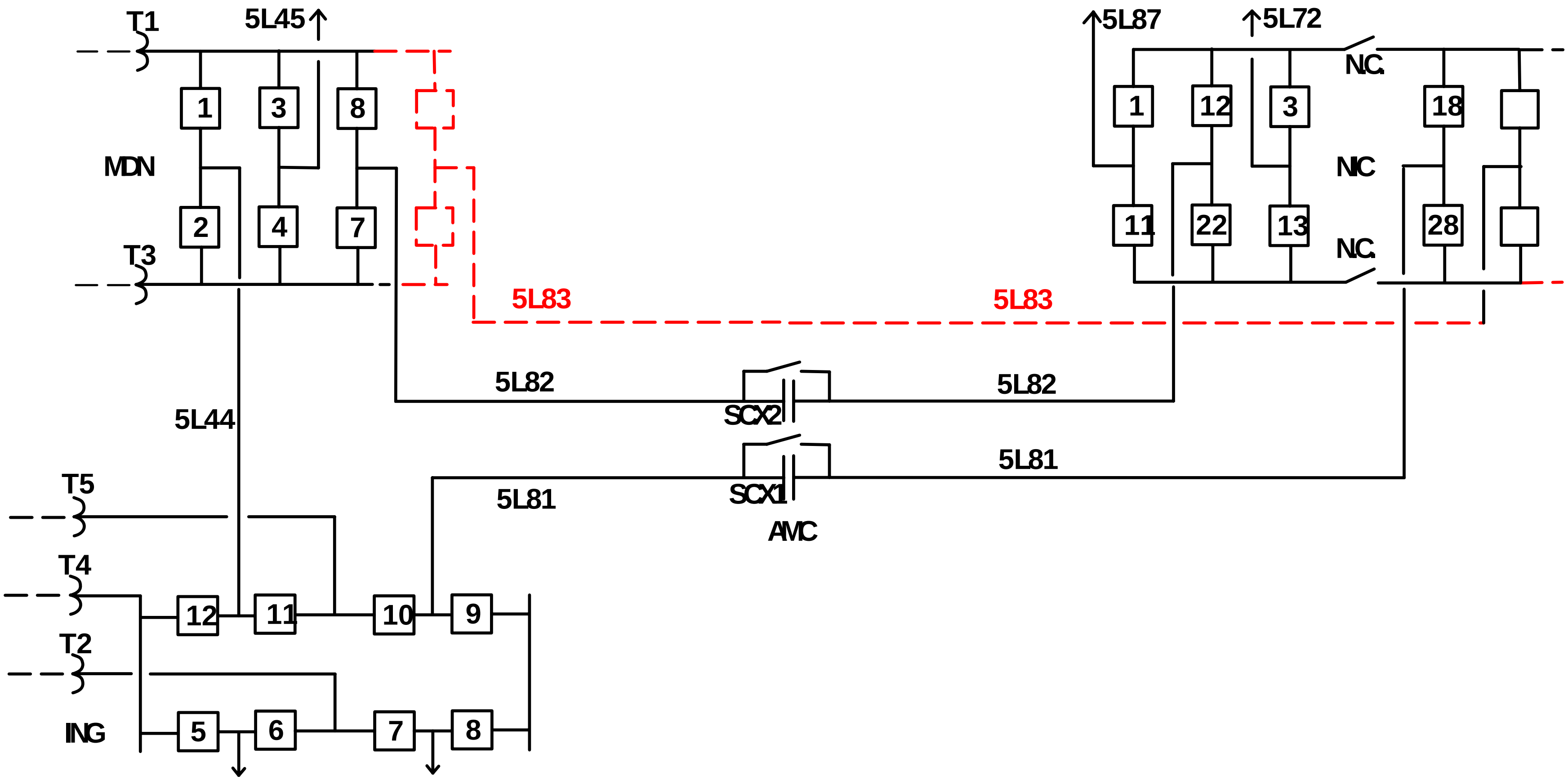

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Figure F-4: Stage 1 of an AC (insulated for dc) to DC bipole to DC tripole development for 5L83.

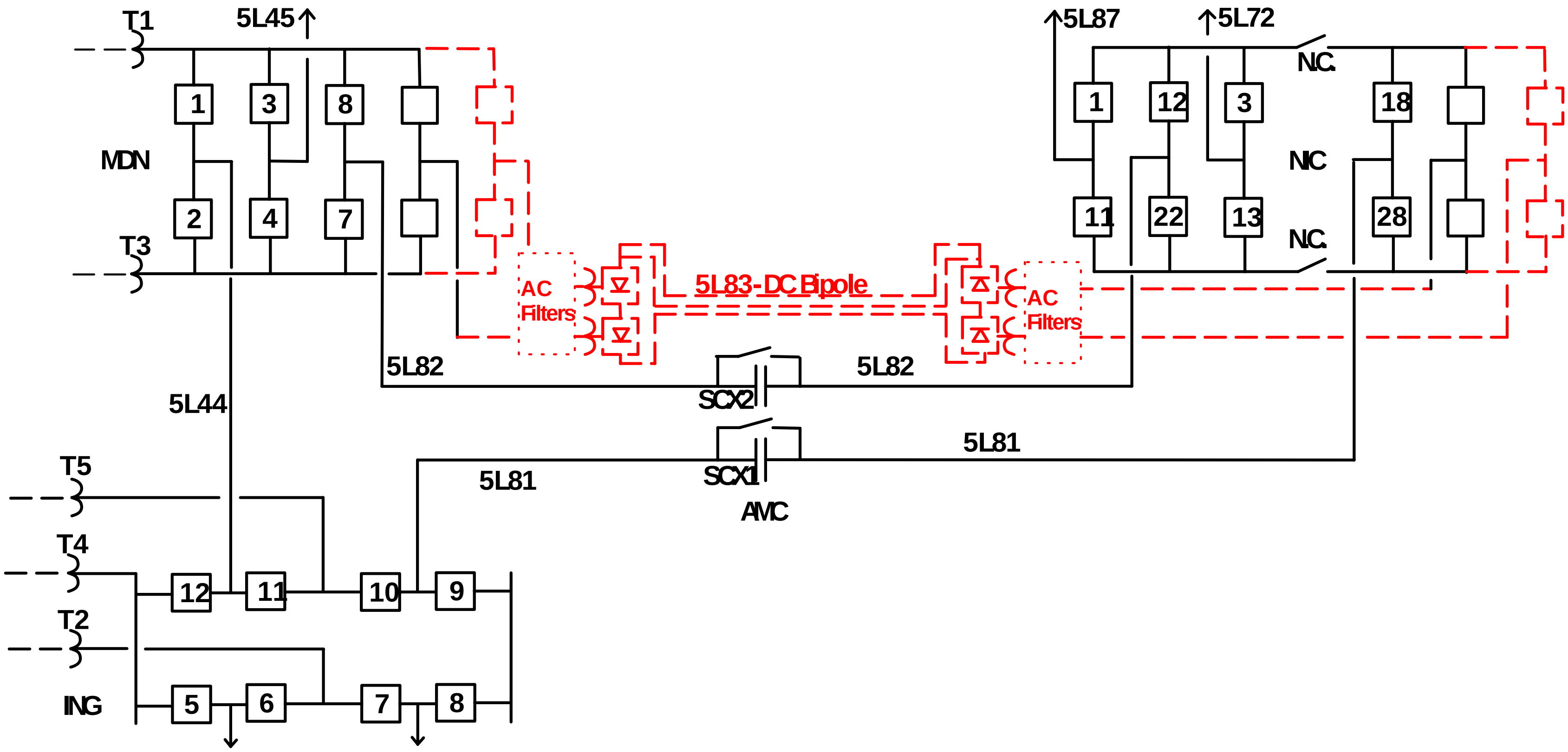

Figure F-5: Stage 2 of a kV AC to DC bipole to DC tripole development for 5L83 (2200 MW operating as a bipole)

Stage 2	MDN DC Converter CDNM_{2007}$	NIC DC Converter CDNM_{2007}$	Total CDNM_{2007}$
Bipole development only	195.8	182.7	378.5
Bipole for future Tripole	204.9	191.9	396.8

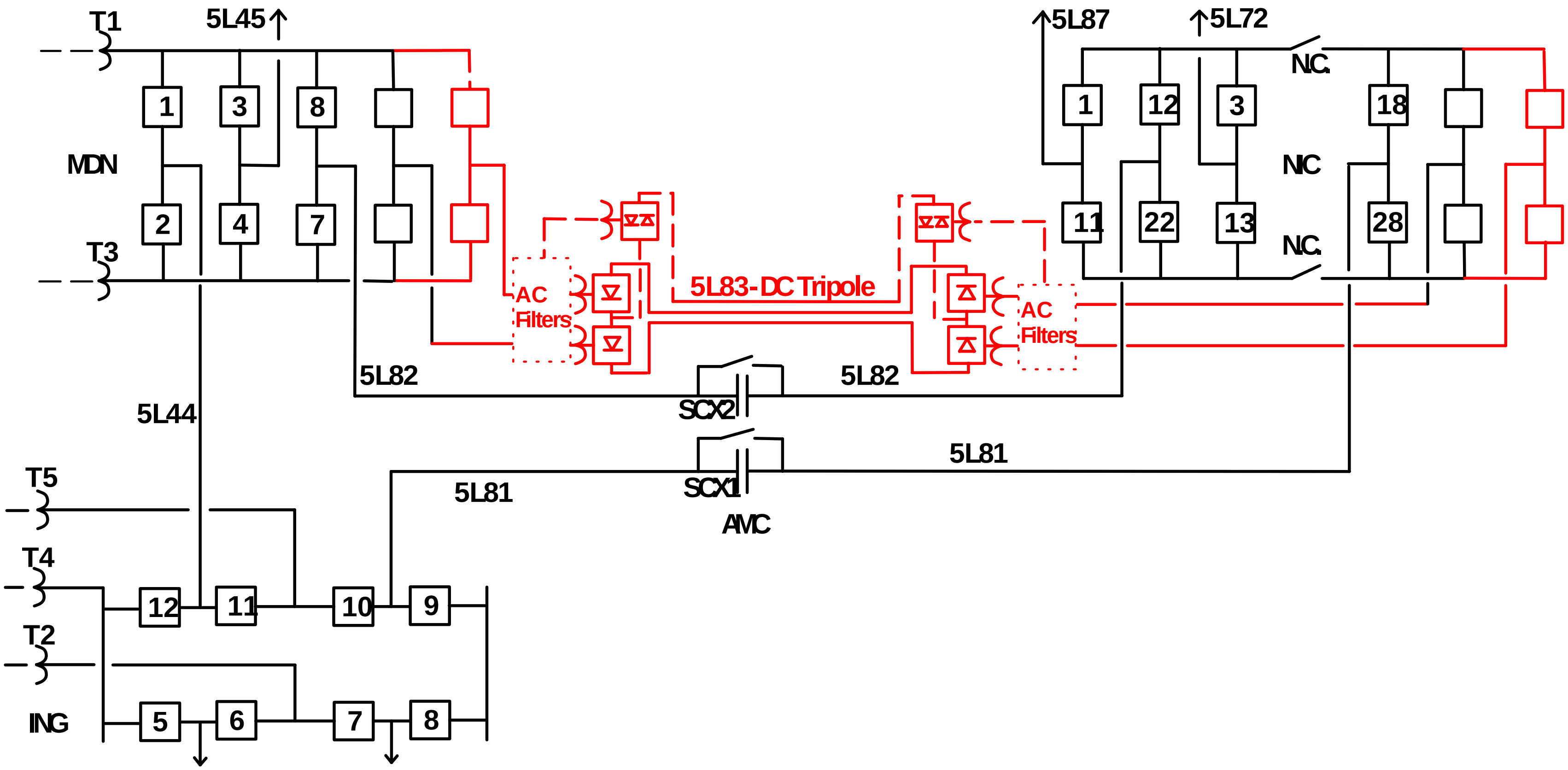

Figure F-6: Stage 3 of a kV AC to DC bipole to DC tripole development for 5L83 (3000 MW operating as a tripole)

Stage 3	MDN DC Converter $CDN\$M_{2007}$	NIC DC Converter $CDN\$M_{2007}$	Total $CDN\$M_{2007}$
Tripole upgrade	106.3	102.5	208.8

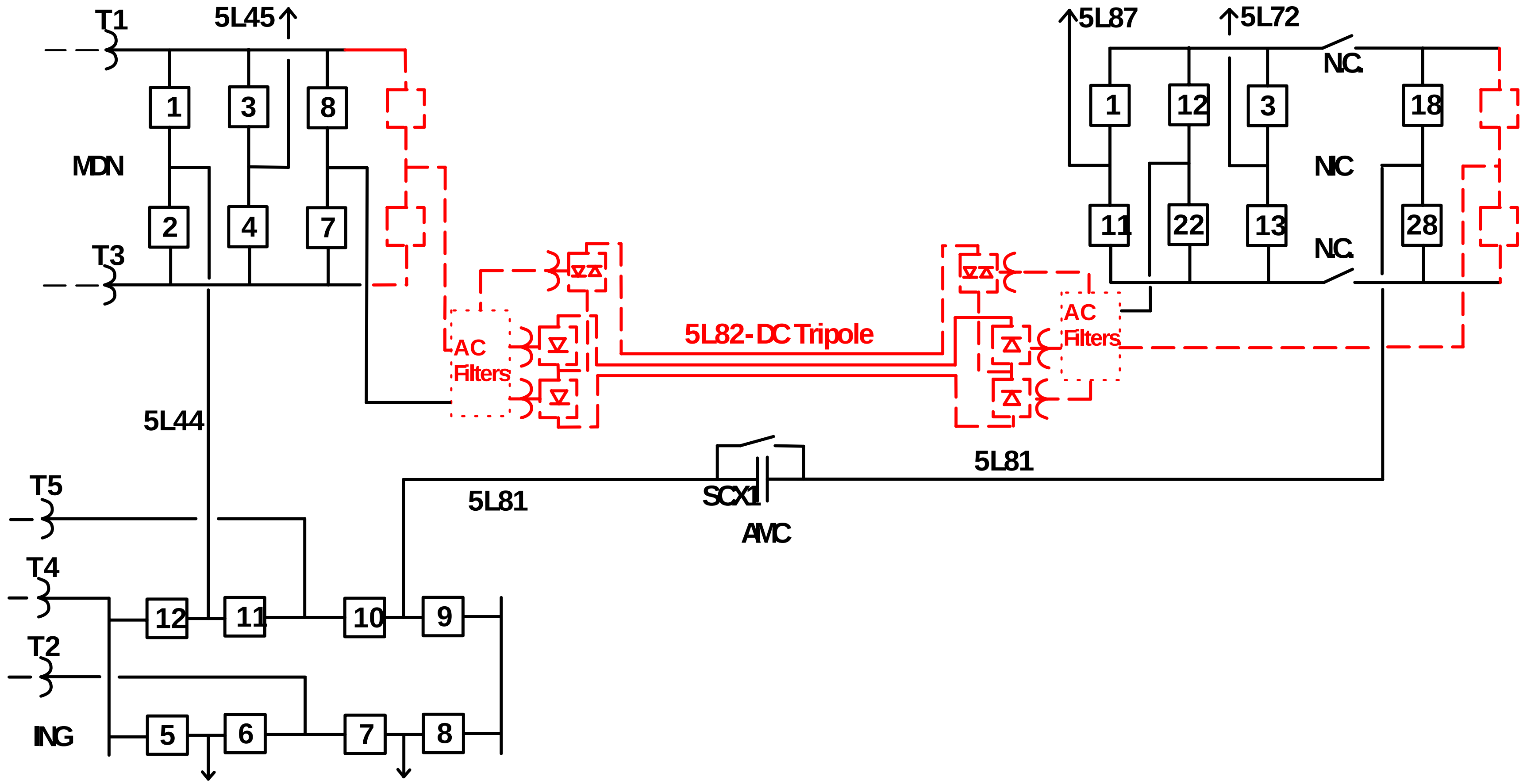

Figure F-7: 5L82 upgraded to a dc tripole. This is a Stage 1 conversion of both 5L81 and 5L81to dc tripole operation.

Stage 1	MDN DC Converter CDNM_{2007}$	NIC DC Converter CDNM_{2007}$	Total CDNM_{2007}$
Convert 5L82 to 2,450 MW Tripole	284.2	269.0	553.2
Convert 5L82 to 3,870 MW Tripole	364.8	345.8	710.6

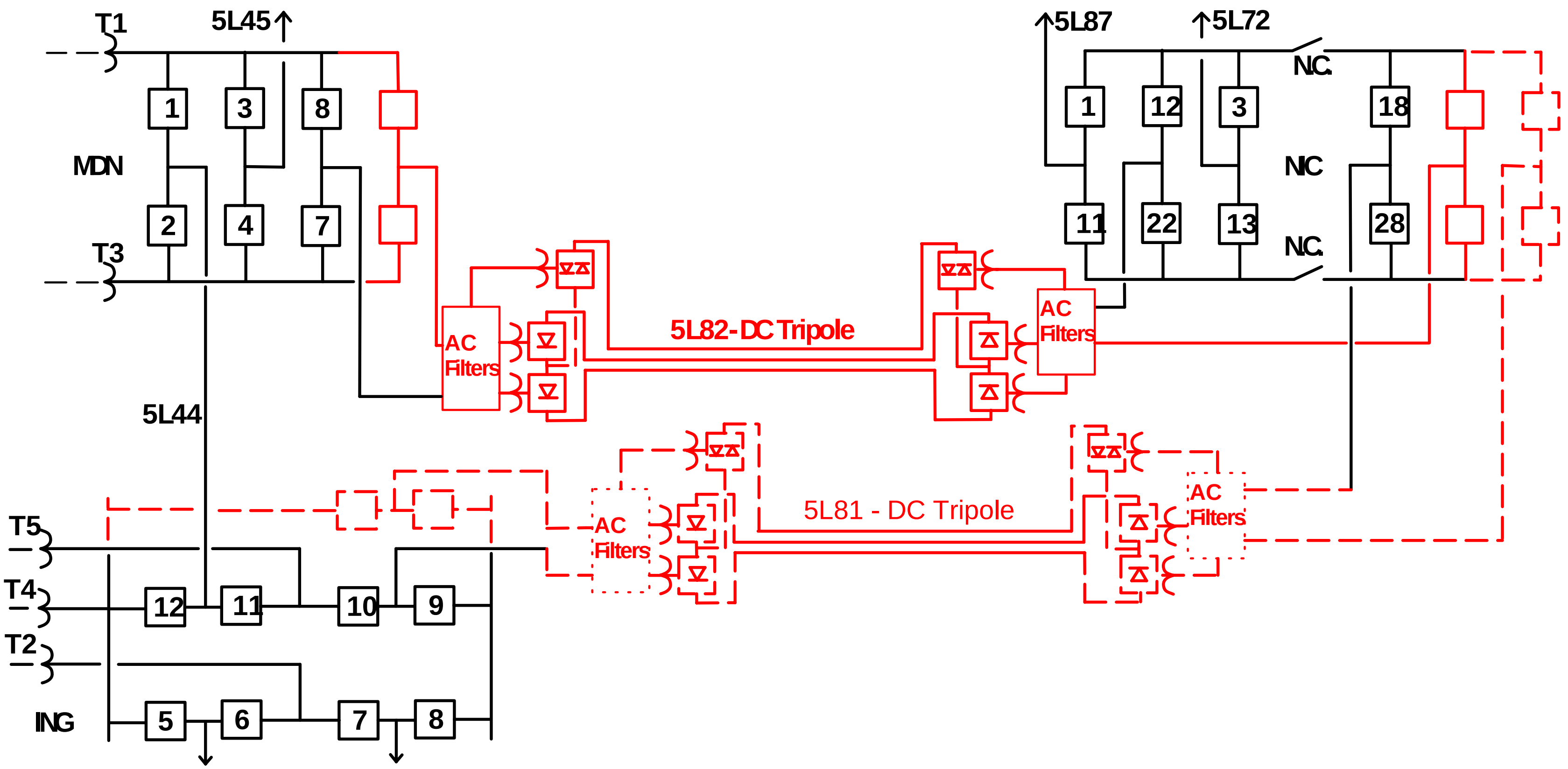

Figure F-8: Second stage of converting both 5L81 and 5L82 to a tripole.

Stage 2	MDN DC Converter CDN\$M$_{2007}$	NIC DC Converter CDN\$M$_{2007}$	Total CDN\$M$_{2007}$
2,450 MW Tripole upgrade on 5L81	284.2	269.0	553.2
3,870 MW Tripole upgrade on 5L81	364.8	345.8	710.5