Forty Years Operating Experience with 300 kV DC Submarine Cable Systems

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Overview of Presentation

- Timing and general description of DC1 and DC2 cable installations
- Vancouver Island supply one-line diagrams
- VI supply geographical layout
- Cable designs and descriptions
- Cable prototype tests
- Electrode descriptions
- Original installation methods
- Operating experience
- Underwater inspections and repairs
- Reliability experience
- Lessons learned
- Current status
Transmission submarine cables to Vancouver Island – Installation Chronology – 1956-1969

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>5 - 138 kV 120 MW SCGF cables commissioned.</td>
</tr>
<tr>
<td>1958</td>
<td>2 – 138 kV 138 kV SCGF cables commissioned, to total 240 MW.</td>
</tr>
<tr>
<td>1969</td>
<td>3 - 280 kV continuous (300 kV short-time) DC, 600 A MI cables commissioned. Maximum rating of a commercial mercury arc valve group at the time was 130 kV, providing 260 kV in series. Firm capacity was 1200 A, 312 MW with one cable out-of-service. Cables operated in a monopolar mode with spare cable used as a metallic return. Spare cable and sea return were operated in parallel if loads exceeded 600 A.</td>
</tr>
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</table>
Complete VI Supply System from Mainland after Commissioning DC1 System, 1969-1975
Transmission submarine cables to Vancouver Island – Installation Chronology - 1975-2008

1975: 2 - 280 kV continuous (300 kV short-time) DC, 900 A SCFF cables were commissioned. New 280 kV, 1320 A, 370 MW thyristor converters added to form a bipolar system. Unbalance current between DC1 and DC2 poles was carried by the spare DC1 cable unless it exceeded 600 A, in which case the sea return was paralleled. In the event of a DC cable failure, one of the 138 kV cables could also be used as a metallic return.

1983: Four 525 kV AC, SCFF submarine cables added to central Vancouver Island to form a 1200 MW circuit.

1984: Two more 525 kV AC cables added to provide an additional 1200 MW circuit.

2008: 3 – 138 kV cables removed and replaced with 3 – 242 kV, 600 MW SCFF cables.
DC2 Submarine Cables
Complete DC Bipolar System Schematic

VANCOUVER ISLAND

SALTSPRING ISLAND

MAINLAND
Present Supply System to Vancouver Island
Schematic Arrangement - 2010
Southern VI HV AC/DC Submarine Cable Locations
Pole 1 - 300 kVdc Submarine Cable System

Figure 3 - Cable route - plan and profile.
DC1 Cable System Description

• The first DC submarine cable system in the Americas, until the recent +/- 150 kV Cross Sound project (New York – Connecticut, 2003), the 500 kV Neptune project (New Jersey – Long Island, 2008) and the 200 kV Transbay project (San Francisco Bay, 2009).
• Cable system supplied by Cables de Lyon (merged into Alcatel, then Nexans France), from their Calais factory.
• Highest voltage continuous DC submarine cables at the time
• ‘Solid Type’, mass impregnated cables
• Cable supply/install contract cost ~ $7M
DC1 Sea Cable

- 400 sq mm copper conductor
- 600A, 300 kVdc ratings
- Oval shape to assist with load cycling expansion/contraction
- Galvanized steel reinforcing tapes over PE jacket
- Each steel armour wire covered with bitumen impregnated cotton tape for superior corrosion withstand
- Transition to larger land cable in shallow water
- Transition jointing done on temporary platform
- Maximum conductor temperature = 55C
DC1 Land Cable

- 650 sq mm copper conductor
- 600A, 300 kVdc ratings
- Oval shape to assist with load cycling expansion/contraction in deep water
- Transition to smaller sea cable in shallow water
- Transition jointing done on temporary platform
- Maximum conductor temperature = 45°C
# Environmental and Cable Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sea</th>
<th>Tidal Area – Roberts bank</th>
<th>Land</th>
</tr>
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<tbody>
<tr>
<td>Maximum water temperature</td>
<td>15 °C</td>
<td>18 °C</td>
<td>-</td>
</tr>
<tr>
<td>Maximum ground temperature</td>
<td>-</td>
<td>-</td>
<td>20 °C</td>
</tr>
<tr>
<td>Assumed depth of burial</td>
<td>0.4 m</td>
<td>0.4 m</td>
<td>0.9 m</td>
</tr>
<tr>
<td>Specific thermal resistivity of surrounding material (°C-cm/W)</td>
<td>40</td>
<td>60</td>
<td>120</td>
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</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>600 A Proposal</th>
<th>1200 A Proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section of conductor (mm²)</td>
<td>Sea</td>
<td>Land</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>650</td>
</tr>
<tr>
<td>Nominal thickness of insulation (mm)</td>
<td>18.5</td>
<td>20.5</td>
</tr>
<tr>
<td>Approx. overall diameter (mm)</td>
<td>91.2</td>
<td>101.6</td>
</tr>
<tr>
<td>Approx. weight in air (kg/m)</td>
<td>25.3</td>
<td>30.6</td>
</tr>
</tbody>
</table>
Prototype Trials

- 8 hr heating cycles to 50 °C followed by 16 hr cooling period
- 20 °C temperature gradient
- 10 cycles of +600 kV
- 10 cycles of -600 kV
- 60 cycle of +450 kV dc with polarity reversals
Cable Laying by ‘Marcel Bayard’ - 1969

- Cable delivered from France and laid by the French Post Office cable ship ‘Marcel Bayard’
- Long mud flats offshore English Bluff Terminal restricted access by laying vessel
- Solution was to use a floating wheel to lay the 4 km section inaccessible by Marcel Bayard
- Cable was transferred onto the scow from the Ocean Layer and then cable was paid out as it was pulled to the landing zone.
Cable Wheel to Float DC1 Cable End to Jointing Platform Offshore Tsawwassen Terminal - 1969

- Floating wheel guiding cable toward shore
- Cable ship stationed about 4 km offshore Tsawwassen Cable Terminal
DC1 Cable - Pulling Land cable from Barge to Tsawwassen Terminal, via Jointing Platform

- Land-sea transition joints were made on temporary platforms with wood piles driven into sea bottom.
DC1 Cable Installation at Parker Island Terminal - 1969

- Land cable floated from barge to shore via splicing platform, prior to arrival of cable laying ship
- Cable laying ship laid sea cable up to splicing platform for connection to land cable
DC1 Cable Installation at Parker Island Terminal
Lifting completed transition joint into water - 1969
DC1 Submarine Cables
Boundary Bay Cathode Design & Installation
DC1 Submarine Cables - Sansum Narrows Anode

Anode Design

Anode Aerial Photo
DC2 Submarine Cable System - 1975

- Submarine cable system supplied by Pirelli Cables & Systems, Milan, from their Arco Felice factory near Naples.
- Land cables supplied by Pirelli Canada from their St. Jean Quebec factory.
- ‘Self contained fluid filled’ cables pressurized with pumping plants at all terminals except Parker.
- Longest self contained fluid filled submarine cable system in the world at the time.
- 2 cables installed in 1975.
- Transmission capacity 270 MVA for each cable.
- Cable supply/install contract cost ~ $13M
DC2 Sea Cable

- 400mm² copper conductor
- 900A, 300 kVdc ratings
- No armour wire covering
- Transition to larger land cable in shallow water
- Transition jointing done on temporary platform
- Maximum conductor temperature = 64°C
DC2 Land Cable

- 650mm² copper conductor
- 900A, 300 kVdc ratings
- Steel armour wires with bitumen impregnated jute bedding and serving
- Transition to larger land cable in shallow water
- Transition jointing done on temporary platform
- Maximum conductor temperature = 65°C
DC2 Insulating fluid pressurizing plant

- Pressurizing plants located on each side of Strait of Georgia
- One pumping plant on west side of Trincomali Channel, with a manual cross-over at the opposite side at Parker Terminal
- Spare fluid pump; remote flow limiting; 8000 gallon fluid storage tank
Cable delivered from Italy to BC on freighter M/S ‘Jota’, then transferred to specially equipped laying barge.

Barge had shallow draft, so was able to approach closer to cable landings than earlier vessels.

No supplementary floating systems were required for sending the sea cable ends ashore, such as the scow or floating wheel systems used for the 138 kVac and DC1 cables.

The sea cable was pulled across the long mud flats in the approach to Canoe Pass Terminal using floats.
DC2 Submarine Cables - Sending Sea Cable End Ashore to Jointing Platform at Parker Terminal - 1975
DC1 - DC2 - Parker Terminal
DC1 Cables Failure Events and Reliability

Route Lengths: 3 – 600 A cables Mainland to Galiano Island - 27.7 km  
3 – 600 A cables Parker Island to Saltspring Island - 3.9 km

Total Cable Length: 94.8 km
Km-yrs in Service: 3792 km-yrs (since commissioning in 1969; 41 x 94.8 – 3 x 94.8/3)

Present Status: Two cables operating satisfactorily. Underwater inspections show evidence of severe armour corrosion in some areas. Cable recovery for repairs may result in additional cable damage. There are also several known underwater cable suspensions that could cause premature failure.

Cable System Forced Outage History:

<table>
<thead>
<tr>
<th>Date</th>
<th>Duration</th>
<th>Affected</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feb. 1970 0.3 Yrs</td>
<td>Cable # 1</td>
<td>External damage occurred prior to burial of cable at north side of ferry terminal, attributed to keel of beached sailboat.</td>
<td></td>
</tr>
<tr>
<td>Sept. 1972 0.3 Yrs</td>
<td>Cable # 3</td>
<td>Cable severed by dragging anchor of a large vessel while manoeuvring on departure from Westshore Terminals dock off Roberts Bank.</td>
<td></td>
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<tr>
<td>May 1990 1.0 Yrs</td>
<td>Cable # 6</td>
<td>Cable fault located directly under a large concrete anchor block.</td>
<td></td>
</tr>
<tr>
<td>June 2007 permanent</td>
<td>Cable # 2</td>
<td>Cable fault located under a large rock near Westshore Terminals off Roberts Bank.</td>
<td></td>
</tr>
</tbody>
</table>
DC2 Cables Failure Events and Reliability

Route Lengths: 2 – 900 A cables Mainland to Galiano Island – 28.9 km
2 – 900 A cables Parker Island to Saltspring Island – 4.3 km

Total Cable Length: 66.4 km
Km-yrs in Service: 2324 km-yrs (since commissioning in 1975; 35 x 66.4)

Present Status: All cables operating satisfactorily. Underwater inspections have shown evidence of severe armour corrosion in some areas. Cable recovery for repairs may result in additional cable damage. There are also several known underwater cable suspensions that could cause premature failure.

Cable System Forced Outage History:

<table>
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<tr>
<th>Date</th>
<th>Duration</th>
<th>Affected</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sept. 1992</td>
<td>0.3 Yrs</td>
<td>Cable # 3</td>
<td>Cable 4 dig-in on land near Canoe Pass Terminal</td>
</tr>
<tr>
<td>Feb. 2002</td>
<td>1.3 Yrs</td>
<td>Cable # 9</td>
<td>Persistent fluid leak in Trincomali Channel</td>
</tr>
<tr>
<td>May 2003</td>
<td>0.5 Yrs</td>
<td>Cable # 5</td>
<td>5 km of cable replaced off east side of Galiano Terminal, due to armour corrosion and potential fluid leak at long suspension.</td>
</tr>
</tbody>
</table>
VI DC Submarine Cable Condition Assessment Activities and Chronology

- Corridor maps were updated and surface sonar, bathymetry and cable location surveys were done in 1995, with an emphasis on identifying possible cable hazards.

- Limited underwater surveys were done in 1995 with a light duty submersible vehicle. Several long cable suspensions were identified at the Galiano Ridge area.

- Additional detailed underwater surveys were done in 1996 and 1997, using an ROV with a water jetting and brushing tool to examine cable armour condition where buried.
VI DC Submarine Cable Condition Observations from 1997 Underwater Surveys

• There were 20 to 41 m long catenaries found on each of the 3 DC1 and 2 DC2 cables located on the west side of Galiano Ridge.

• There was advanced armour damage at the catenary touch down point on DC2 Cable 5 (1 - 2 wires broken).

• In water depth < 20 m offshore Galiano Island, DC2 Cable 4 and 5 armour wires were severely corroded where exposed on the seabed, but were in good condition if covered with silt.

• Elsewhere in Trincomali Channel and in Georgia Strait, the cable armour was in good condition where naturally buried in bottom sediments.
DC2 Cable 5 Profile at West Side of Galiano Ridge
(as determined from 1997 survey)
1997 Condition of DC2 Cable 5 at Bottom of Long Suspension at Galiano Ridge
1997 Condition of DC2 Cable 5 at Top of Long Suspension at Galiano Ridge
• Condition assessment report was issued in 1998, concluding that:
  – Cable armour was in good condition for about 80% of route, where the cables were naturally buried in the bottom silt.
  – Elsewhere in the shallow waters (< 20 m deep) off the west side of Georgia Strait and in Trincomali Channel, and in the vicinity of the Galiano Ridge, the DC2 cable armour is severely corroded.
  – Armour corrosion was advanced in areas where cables made transition from buried to unburied state, notably at the bottom of Galiano Ridge and in Trincomali Channel.
  – There is a high risk of failure at the Galiano Ridge catenaries.
  – Other cable components (jacket, sheath, insulation) are in good condition.
  – Remaining cable life was estimated at about 30 years, assuming replacement of 20% of route, at a cost of about $30M, if done all at once.
Top and Bottom Cable Touchdown Points at Galiano Ridge
DC2 Cable 5 February 2003

Top touchdown

Bottom touchdown
Cutting and Capping of DC2 Cable 9

- In 2001 efforts were accelerated to locate a slow leak in DC2 Cable 9 in Trincomali Channel, using high resolution sonar and a submersible vehicle.
- After many unsuccessful attempts, the cable was abandoned when leak rates became excessive.
- Cable ends were cut and capped on shore and insulating fluid was replaced with water pumped in one end, while fluid was expelled from the other.
Results and Conclusions from 2001 DC2 Survey

• 2001 inspection of the Galiano Ridge DC2 Cable 5 top suspension touchdown point showed armour wire corrosion had visibly advanced since the 1997 inspection.
• In September 1997, there were only 1 - 2 broken armour wires at the top touchdown point, compared to about 5 in September 2001.
• The cable armour cross-sectional area had become significantly reduced and armour weakened.
• Loss of armour wires could cause twisting of the cable and sheath tearing.
• Abrasion resulting from even slight cable movement due to tidal currents, could cause damage to underlying components (anti-corrosion jacket, sheath reinforcing tapes, lead sheath).
• There was evidence of some cable movement.
• There was deemed to be a high risk of Cable 5 sheath failure at any time, resulting in oil leaks into the sea.
• Therefore, a decision was made to replace Cable # 5 from the shore to beyond the Galiano ridge damage area.
• Cable # 9 was restored during the same campaign.
Recovering Land/Sea Joint Frame from near DC2 Cable 9 Trincomali Terminal

- DC2 Cable 9 replaced in May 2003 due to a persistent, unlocatable leak.
- During removal of one of the land-sea transition joints, evidence of the fluid leak was found.
- Severe armor corrosion had occurred within the joint casing.
Tests on 34 year old spare cable and joints for replacement of DC2 Cable 9 in Trincomali Channel

• No significant anomalies in the hydraulic, chemical, and electrical tests were uncovered. The cable was deemed to have passed all the tests.

• Condition of fluid extracted from the spare HVDC cable was found to be in reasonable compliance with factory requirements.

• 31 year old containers for the paper rolls for spare terminations and joints were found to have O-ring seal leaks, resulting in high levels of water in impregnated paper rolls. All had to be replaced.
2007 DC1 Cable Failure

- A spontaneous failure occurred in DC1 Cable 2 on 4 June 2007.
- TDR tests provided an approximate location offshore Tsawwassen Terminal.

- An ROV survey found a large rock sitting on the cable, suspected to have been dropped during construction of a nearby container terminal.
Strategy for DC1 Cable 2 repair/abandonment action

- Cable tests showed the measured fault resistance (insulation resistance) to be very low (~ 0.15 Ohms).
- However insulation at the fault site was sufficiently compromised to prevent using Cable 2 as an effective metallic neutral, although the conductor appeared to be intact.
- All considered, a decision was made to not repair DC1 Cable 2, since capacity was available on the new 230 kV ac circuit.
- Remaining life of DC1 converters was also believed to be short.
Lessons Learned: Cable protection from transient over-voltages

– Lightning arrestors not used at cable terminals.
– Instead relied on self protection arising from differing surge impedances between overhead and cables (300 Ω vs. 20 Ω)
– Most of the incident lightning impulse is reflected back at terminations, with only partial transmission into cable.
– Transmitted ‘traveling wave’ impulse is attenuated over long cable length.
– No cable failures attributable to transient over-voltages.
– The area has low keraunic levels.
– Lessons learned: For long submarine cables, surge arrestors can probably be safely eliminated for most applications. However, they provide low cost ‘insurance’ protection from unconventional transient over-voltages, so have been applied for newer circuits.
Lessons Learned:
Different sized land and sea cables

– Almost always a potential thermal bottleneck on land if the same sea cable conductor size is used throughout, because cables usually need to be more closely spaced on land.
– Choices are:
  • Maintain wide spacing up to terminals, if possible
  • Install in tunnel up to terminals, if possible
  • Use forced cooling system for land section.
  • Use larger sized land cables with permanently wet transition joints,
– DC1 and DC2 successfully used the latter system.
– However, it is believed that one of the eight DC2 transition joints experienced an insulating fluid leak, ultimately leading to cable replacement.
– Lessons learned: Avoid transition and field joints if possible.
Lessons Learned:
Applying new technologies

– Both DC1 and DC2 applied higher DC voltage levels than ever before, with long continuous cables without joints.
– Thorough development tests, type tests and routine tests were developed, in the absence of industry standards, guides or technical brochures.
– Success was due to a very innovative cable manufacturing industry and a high degree of engineering involvement by power utility engineers.
– Since DC1 and DC2 commissioning, cable voltage levels have doubled and transmission capacities quadrupled, through continuing efforts by industry.
– Lessons learned: Cable industry standard tests are conservative. Power utilities should not be afraid to try state-of-art designs, provided thorough engineering is applied throughout.
Lessons Learned:
Reliability Highlights

- Both DC1 and DC2 cable systems have been very reliable over their service period, compared to other HVDC submarine cable systems and converters.
- No DC1 or DC2 cable failures due to internal defects.
- No DC1 or DC2 cable termination failures.
- One DC2 cable joint failure (resulting in fluid leak and ultimately replacement of 4 km long Cable #9).
- One DC2 cable replacement due to corrosion (5 km of Cable #5).
- Five cable failures due to external aggression (DC2 sailboat keel, DC2 dig-in, DC1 anchor, two DC1 dropped rocks/blocks).
- Cable system reliability is considerably better than statistics described in Cigré Technical Brochure 379 ‘Update of Service Experience of HV Underground and Cable Systems’, April 2009.
- Lessons learned: Good mapping and education of marine pilots and ferry captains appears to have been effective at limiting third party damage. But some failures must be expected.
Lessons Learned: Armour Corrosion

- Corrosion has been most severe where cables transition from buried to unburied conditions.
- Armour wire corrosion may ultimately determine end of cable life, as loss of cable tensile strength will make recovery for reliable repairs difficult.
- DC1 cables had each galvanized steel armour wire wrapped in bitumen-saturated fabric tapes.
- DC2 cables had bare galvanized steel armour wires.
- Underwater inspections have shown the DC1 cables to be more resistant to corrosion.
- BCTC/BC Hydro has successfully retrofitted impressed current cathodic protection systems to DC1 and DC2 armour systems, and surveys show that it is functioning as planned.
- They have also been retrofitted to the VI 525 kV submarine cables and were incorporated into the 242 kV submarine cables to Vancouver Island.
- Lessons learned: With relatively small effort, CP systems can be applied to submarine cable armour systems, to mitigate one of the leading threats to submarine cable longevity.
Conclusions and Present Status

- The BCTC/BC Hydro HVDC submarine cable system to Vancouver Island successfully applied state-of-art HVDC cable technology.
- Approximately 40 years of satisfactory performance has been achieved, with additional life expected.
- The cable systems are a testimony to the innovation of the cable engineers and technicians responsible for original design, manufacturing and installation.
- Technology improvements since commissioning suggest better performance for new HVDC cable systems.
- Plans are to soon retire the Pole 1 converters, since maintenance costs for the mercury arc valves are excessive and there is now alternate transmission capacity.
- The remaining two DC1 cables will continue to be used normally as metallic returns with DC2 operating in monopolar mode.