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HVDC VSC (HVDC light) transmission – operating experiences

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SUMMARY

High Voltage Direct Current (HVDC) with Line Commutated Converters (LCC) was developed and put in commercial operation already in the 1950's, with mercury arc valve technology. In the 1970's, HVDC applications evolved with the introduction of thyristor based valves, which have over the years proven highly reliable, and well studied in Cigre's collected statistics and sessions. HVDC's typical applications are long-distance "bulk-power" transmission inter-connectors and long submarine cable systems. The development of power electronics technology resulted in the mid 1990's of a new type of valves for the HVDC converters based on transistors (e.g. utilising Insulated-gate Bipolar Transistor, IGBT), called Voltage Source Converter, VSC.

HVDC Voltage Source Converter (HVDC VSC)

The developed HVDC VSC technology can be utilised for a much more elaborate and fast control of the valves. One of the most important new features compared with LCC is the functionality to not only control the real power flow MW but also the reactive power, i.e. the voltage level, at both connections, also referred to as the STATCOM or SVC (Static Var Compensator) functionality. HVDC VSC even allows for start up of complete "dead" AC systems ("black-start capability"). The global trend shows VSC projects with continuously increased capacities up to 1,200 MW. New applications include large wind farm connections, supply to urban load centres, and connections to remote "weak" AC systems. HVDC VSC technology allows overhead lines or land cable systems, i.e. underground solutions, the latter application of special interest for environmental reasons and easement of the permit process.

A number of HVDC VSC transmission installations, both globally as well as here in Australia, have now been in operation for quite a few years. This paper, to our knowledge, covers the first study of the operation experiences from this relatively new technology. Two HVDC VSC transmission links have been studied, both with 7 years of operation, although in quite different conditions. The two VSC links comprise one installation in the US with submarine cables and one in Australia with land cables, thereby widening the areas of interest. The available statistics for the 7 years operation for the respective installations' availability and reliability are presented as a measurement of the operation performance. This presentation of HVDC VSC performance provides useful information for system planners to compare available transmission solutions based on actual operation experience. In addition, it should be of interest for the requirements for new HVDC VSC projects.

KEYWORDS

HVDC, Voltage Source Converter, HVDC Cables, HVDC Operation, HVDC Performance

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Background - The Voltage Source Converter

When the Murraylink and the Cross Sound Cable (CSC) projects were commissioned in 2002, there had already been a number of projects with VSC technology in operation. Due to the fast development pace within this relatively new area of transmission technology, this was the second generation of HVDC converters, introducing three-level converter valves with active neutral-point clamping. This evolution of the concept led to a large reduction of losses, from 3% to approximately 1,7% per converter station. At the same time IGBT technology had advanced and led to the introduction of a third generation of presspack IGBTs with up to three times the current rating compared to the ones used in Directlink. Another important step in the development of VSC transmission was the premiere for commercial HVDC application of third harmonic addition to the converter output voltage, used in CSC. This technique increases the voltage output by 15% given the same direct voltage. It all combined to lift the VSC technology from sub-transmission and distribution to power levels suitable for transmission systems.

Project name	Country	Application	Rating MW or MVA	Year of commis-sioning	DC Voltage [±kV]	Converter type
Hällsjön	SE	HVDC	3	1997	10	2-level
Hagfors	SE	SVC	±22	1999	10	3-level diode clamped
Gotland	SE	HVDC	50	1999	80	2-level
Tjaereborg	DK	HVDC	7	2000	10	2-level
Moselstahlwerke	DE	SVC	±19	2000	20	3-level diode clamped
Eagle Pass	US	HVDC Back-to-back	36	2000	18	3-level diode clamped
Directlink	AU	HVDC	3x 60	2000	80	2-level
Murraylink	AU	HVDC	220	2002	150	3-level actively clamped
Cross Sound Cable	US	HVDC	330	2002	150	3-level actively clamped

Table 1: VSC converters in operation 2002

The converters in VSC transmission differs from the classic line-commutated converters in several ways. One important feature that increased the field of application of HVDC greatly is the ability to control reactive power and active power independently and to act as a virtual generator in a network that otherwise lacks generation. Another important aspect is the ability to change power direction without voltage reversal. It also enables the use of polymer extruded cables suitable for both sea and land application, as demonstrated in the two projects reported here.

With series connection of IGBTs in the valves one crucial parameter is the ability to conduct current even in the failed state, the so-called Short Circuit Failure Mode. This has worked flawlessly for a commercially operating base of 28,000 presspack IGBTs for a total of 222 converter years (figures for October 2009).

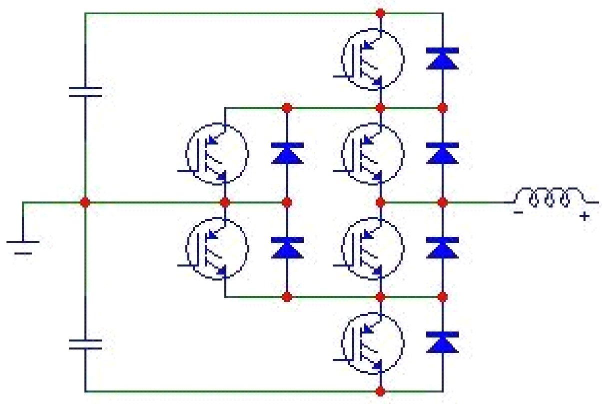

Figure 1: Three-level converter principal circuit diagram for one phase. Each IGBT / diode symbol is in reality made up of more than 150 presspack IGBT modules in Cross Sound Cable and Murraylink.

Technical Background – HVDC VSC Cables

The installation of the Murray Link underground cable sounded the bell for a new era in cable technology. Although HVDC land cables had been used since many decades [3], the Murray Link cable system was the first modern extruded HVDC cables rated for 150 kV.

Underground power cables always have been regarded as heavy, difficult to install, and prone to faults. Many underground cables were filled with oil, requiring complicated oil pressure plants. Especially the cable joints sometimes were cumbersome, residing in bulky concrete manholes and calling for frequent maintenance. Leaking cable oil created a bad reputation.
The extruded HVDC Light cable installed for the Murray Link project eliminated virtually all disadvantages associated with long-distance underground cable systems. Fig. 1 shows a telescopic view of the Murray Link HVDC cable. The aluminium conductor is both more economic and more lightweight than a copper conductor. A triple-extruded insulation system with 12 mm insulation thickness enables a fast production process.

Figure 2 Telescopic view Murraylink cable

The insulation system with inner semicon, insulation wall and outer semicon is made from materials specially designed for DC applications. The design temperature is 70º C. Over a 30 mm^2 copper screen the radial water blocking system is applied, consisting of a layer of swelling tape and a watertight aluminum/poly-ethylene laminate. Finally an HDPE jacket is extruded as outer protection.
The transmission capacity of a pair of HVDC Light cables (220 MW) can be matched only by a conventional three-phase cable system with approximately 3x1200 mm^2 copper conductor area. The lightweight cable with a little more than 10 kg/m is very suitable for the installation in rural areas where roads sometimes have limited load-bearing capacity. Before the final design of the conductor size was settled, a comprehensive survey of the soil thermal resistivity was performed along the cable route. For each route section with its particular thermal environment the most economic conductor size could be determined. But in an over-all assessment it became clear that the advantages of easy logistics and spare part keeping with only two conductor sizes outweighs the small savings of sub-optimised conductor design. It was decided to produce the Murray Link cable with two conductor sizes, 1200 mm^2 and 1400 mm^2, respectively.

The cable joints

The ease of installation and high reliability were key targets in the development of the pre-molded pre-tested HVDC Light cable joints. The joints are completely dry and maintenance free. The conductor connection was realized using a screwed conductor connector. A patented non-linear resistive stress control system is integrated into the EPDM (Ethylene Propylene Diene Monomer) joint sleeve. Since the same joint sleeve could accommodate cables with either conductor size, only one joint sleeve size was necessary for the Murray Link. Only the conductor connectors were customized to the different conductor sizes.
It is one of the features of HVDC systems that there are no circulating currents in the cable screen. No cross-bonding schemes with costly link boxes and sheath voltage limiters were needed. A simple bare copper line in the underground joint area was used for grounding the cable screen wires in each joint.

Figure 3 Elastomeric dry HVDC Light cable joint

After assembly the joints were simply lowered onto the bed of cable sand and covered with backfill material. No underground concrete structures or overground structures were needed.
The assembly of the joints could be made in an efficient process interleaved with the cable laying, or post-lay. Today, this method has been developed to a semi-industrial fast process in a local dry and clean environment. Although almost 400 joints had been installed in the 177 km of cable route, not a single one have failed during operation 2002 – 2009.

HVDC VSC Cable Testing and installation

The type tests for the Murray Link cable were performed referring to the Cigré recommendation for testing of extruded DC cables [4], which was under development at that time. Manufacturing and testing of the Murray Link cable is described in larger detail in [5].

The Murraylink cable system could be installed with unprecedented speed thanks to purpose-built installation machinery and user-friendly design of the cable joints. Very stringent environmental requirements could be met, and exceeded. The installation won the 2002 Case EARTH Award for Environmental Excellence for best practice and innovation in the environmental management of civil construction projects

HVDC VSC Cross Sound Cable Project (CSC) - Background

TransEnergie US (TEUS), a division of Hydro-Quebec (H-Q), was selected by the Long Island Power Authority (LIPA) as the winner of their March 2000 RFP for an Off-Island Transmission Interconnection. This project was named the Cross Sound Cable (CSC). TEUS, through its Australian subsidiary, TransEnergie Australia was already involved in constructing the DirectLink project [1] in Australia. TEUS awarded an engineer-procure-construct contract to the same manufacturer with the challenge to build the voltage source converters to handle more than five-times the power transfer at nearly twice the DC side voltage. The manufacturer responded with the first use of their second generation, voltage source converter design that would feature a +/- 150kV, three-level, IGBT converter valve rated to receive 330 MW, a larger modular design and a 40km, HVDC submarine cable system. Some of the key reasons for selecting the VSC-based converters and solid dielectric HVDC, submarine cables are:

- Solid dielectric submarine cables, no oil, fast installation
- Modular converter design, factory testing, fast installation and testing
- Continuous, independent control of real and reactive power
- Ability to meet performance requirements by interconnecting utilities
- Remote control and monitoring, no full-time staff on site

CSC was commissioned in August 2002 [2] after a short, nine-month construction period. The Halvarsson Converter Station is located in New Haven, CT and the Tomson Converter Station is located in Shoreham, NY. There were disputes ongoing with various permit and regulatory authorities regarding the burial depth of the cable, which prevented full commercial operation. CSC was a valuable resource for Long Island (Figure 4) during the recovery from the August 14, 2003 blackout. The US Department of Energy ordered CSC into operation to assist Long Island. CSC continued to operate under the order until May 2004. During this time period, all parties involved in the dispute reached a settlement and full commercial operation began in late June 2004.

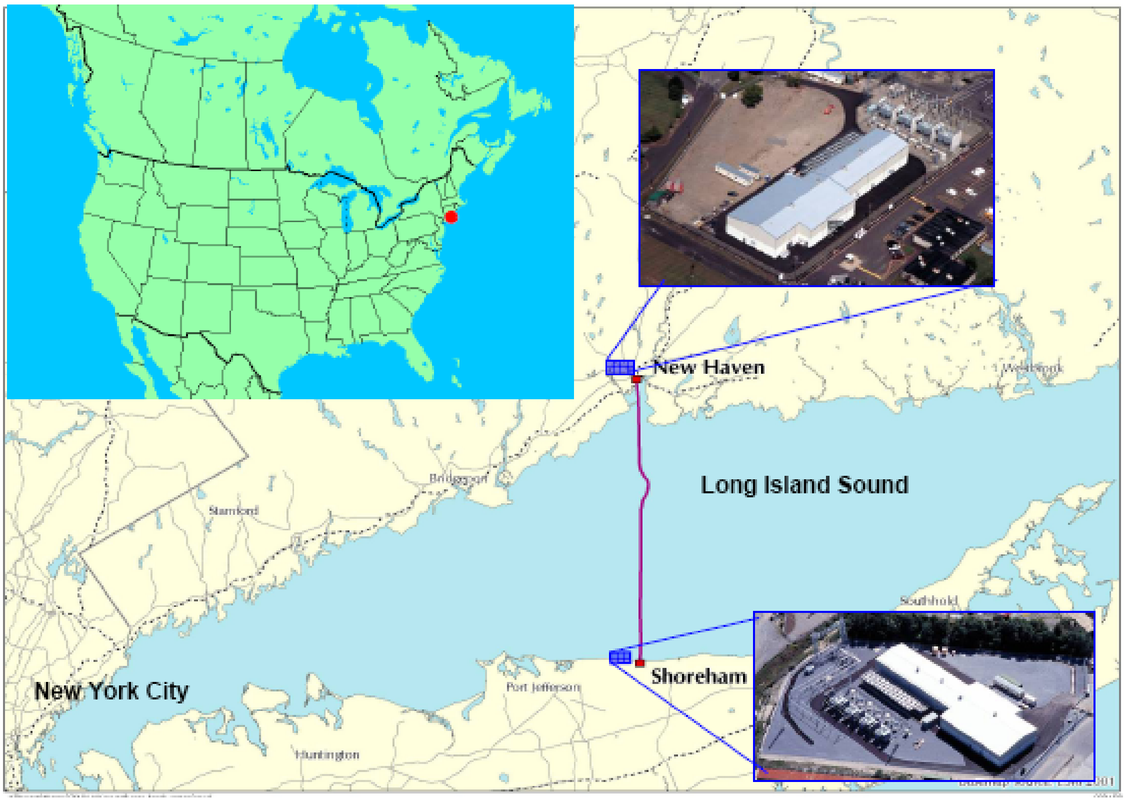

Figure 4 – Geographical location of Cross Sound Cable

Cross Sound Cable - Operations

CSC's corporate headquarters and 24/7 operations center are located in Westborough, MA. The converter stations are remote controlled via T-1 telecommunications lines and the submarine fiber optic cable connected between the converter stations. CSC O&M, staff perform a minimum of a weekly inspection at each converter station. CSC O&M staff also handle 24/7 emergency call-out, routine maintenance and fault tracing. CSC's O&M staff is supplemented by a number of contractors via annual service agreements. A key contactor is a marine support and service provider for repair of the submarine cable system.

The manufacturer's design target for the annual forced outage rate is 1.18% (103.6hrs), and it is 0.82% (72hrs) for the scheduled outage rate. The forced outage rate has been within the 1.18% target except for a major event in 2004 and in 2009. The scheduled outage target rate of 0.82% has been difficult to meet due to upgrades and unexpected repairs.

Table 1 provides a summary of the forced outage rate, the scheduled outage rate and energy availability for the period from Aug 2003 through Nov 2009. Each year is reported from Jan 1 – Dec 31 except for 2003 (Aug – Dec), 2004 (Jan-Apr, July-Dec) and 2009 (Jan – Nov).

All of the forced outage events have been investigated by the CSC O&M staff with support from the manufacturer where needed. The largest forced outage event occurred in Nov 2009 and was due to a maintenance error where an aerial lift contacted a 200kV bus bar causing damage to station post insulators. This caused a seven-day outage while replacement station post insulators were sourced, delivered and installed. Failures of the circuit breaker mechanisms, the re-work to the 220kV cables and cable terminations, and unnecessary protection trips were the largest source of the remaining forced outage time. Converter protections have responded to trip the converter for remote ac network faults on numerous occasions. Each one of these trips is investigating to determine if the protection settings can be improved to reject similar remote faults in the future.

Year	Forced Outage (%)	Scheduled Outage (%)	Energy Availability (%)
	Target is 1.18%	Target is 0.82%	Target is 98%
2003	0.74	0.69	98.57
2004	2.73	0.67	96.60
2005	0.93	0.96	98.11
2006	0.12	1.17	98.71
2007	0.81	4.03	95.16
2008	0.93	3.60	95.47
2009	1.87	2.34	95.79

Table 2 – Summary of Forced Outage, Scheduled Outage and Energy Availability
Highlights for each year are provided below:

Some comments to the statistics;

- 2003; Forced outage items included a leak from a valve cooling heater, faults in IGBT valve control boards and converter protections that were set too sensitive or had timing coordination issues. The scheduled outage items were includes the annual scheduled maintenance.
- 2004; Forced outage items included a trip due to a camera flash near the valve control, a faulty pressure relay on a tap changer, corona indoor DC disconnectors due to contamination.
- 2006; Forced outage items included a maintenance error on the protections and converter protections that were set too sensitive or had timing coordination issues. The scheduled outage items were for the annual scheduled maintenance, software revisions, repair to the overhead indoor crane, repair to hot spots found during FLIR (Forward Looking Infra Red) inspection and replacement of IGBTs.
- 2009; Forced and scheduled outage items included a faulty detection of a Buchholz relay trip by a digital input board, a maintenance error that damaged station post insulators and converter protections that were set too sensitive or had timing coordination issues. The scheduled outage items were for the annual scheduled maintenance and repair of a faulty conservator tank oil level indication.

Cross Sound Cable - Performance of the IGBT (stack-pack type)

There are 2,916 IGBTs in service at each converter station. These IGBTs are designed to fail-safe as a short circuit. An IGBT position monitoring feature reports the exact location of each IGBT that has failed to report back to the control system. The trend for the failures of the IGBT power electronic for the period from July 2003 through November 2009 is presented in Table 3 below.

	Halvarsson Converter	Tomson Converter	Total
Period	IGBT Failures	IGBT Failures	IGBT Failures
	Target is 14.6/yr	Target is 14.6/yr	Target is 29.2/yr
July 2003 – June 2004	16	18	34
July 2004 – June 2005	11	10	21
July 2005 – June 2006	14	8	22
July 2006 – June 2007	2	4	6
July 2007 – June 2008	2	4	6
July 2008 – June 2009	5	4	9
July 2009 – Nov 2009	2	5	7

Table 3 – Summary of IGBT Module Failures

Cross Sound Cable - Summary

Cross Sound Cable was the first use of the manufacturer’s second generation of voltage source converters for transmission systems. The significant increase in power transfer and DC operating voltage did create some unforeseen design and operations issues. In some cases, these issues have caused forced outages or required scheduled outage to install revisions. CSC works closely with the manufacturer to resolve these issues.

HVDC VSC Murraylink - Background

The Murraylink project was conceived as a market network service in the Australian national electricity market. To participate as a market network service provider, it was necessary to have accurate control of active power transfer, independent of power flows over the connecting AC transmission lines. Accurate control of AC network voltage was also required to enable the installation of a transmission line without the need for AC network augmentations. For both these reasons, the HVDC light technology was chosen.

The Murraylink project consists of two converter stations, one located at Berri in South Australia and the other located in Red Cliffs in Victoria. The DC cables are installed underground for 180km between the converter stations. The project was commenced in 2000 and in operation in 2002.

Figure 5 - Berri Converter Station

Murraylink - Operation of the converters

The active power dispatch is determined by the Australian Energy Market Operator (AEMO) with the objective of balancing generation, transmission and load to achieve a lowest cost market outcome. The active power dispatch can change as frequently as every five minutes for extended period of time. Consequently, the energy utilisation of Murraylink is highly variable and not effective as a measure of performance. Instead, the main measure of performance applied to Murraylink is availability. Generally the availability is improving with time though there have been some significant equipment faults that impacted the availability in 2005 and 2007.

Energy Availability	2003	2004	2005	2006	2007	2008	2009
Total	95.18%	97.08%	95.39%	98.92%	90.56%	99.17%	99.37%
Scheduled	96.49%	98.77%	97.96%	98.51%	97.91%	99.12%	99.13%
Forced	98.21%	98.04%	97.11%	99.33%	90.98%	99.86%	100.00%

Table 4 - Energy Availability Murraylink

Comment related to table 4 above and the 2007's low number;

- The 2007 forced availability was reduced by a single long outage after a fault in the phase reactor, most likely caused by an external fault in a light fixture above the reactor that lead to a fire on top of the Phase reactor. The repair and replacement work took extra long time as the converter building was not designed to accommodate an easy replacement or to contain the contamination from the fire which caused significant cleaning.
- With exception of 2007, average for Forced Availability is close to or exceeds the 98% level.

Murraylink - Operation of the cable system 180 km

Murraylink had a single cable fault shortly after commissioning. No cable faults or cable joint faults have occurred since. The installation of the cables underground provides several advantages as follows.

- The cables required a corridor only 4 metres wide and consequently could be installed within public land such as road reserves with minimal need to acquire easements over private landholdings.
- The underground cables had no visual impact which facilitated community acceptance of the project.
- The narrow corridor minimised the environmental impact and enable the cables to pass around environmentally significant areas.
- The underground cables are unaffected by lightning and fire.
- Murraylink engages with the community by participating in the national referral service for underground cables and pipes called Dial-Before-You-Dig.

Murraylink - Benefits for the adjacent transmission system

Murraylink is installed in a weak part of the Australian transmission network. Whenever Murraylink is operating, the converter stations are set to control a constant AC voltage, effectively performing the function of an SVC, in addition to transferring active power.
To enable greater power transfer by Murraylink during heavy loading of the AC network, a number runback schemes have been put in place. The rate of active power reduction varies depending on the monitored AC network element. The fastest reduction rate is 120,000MW per second, which is achieved while maintaining a stable AC voltage control of the adjacent AC network.

Murraylink - Summary

The main measure of performance applied to Murraylink is availability. The overall availability of Murraylink continues to improve. Where equipment faults have occurred, maintenance activities have been adjusted to prevent future recurrence of similar faults.

The training and documentation has proven generally sufficient for the operation of Murraylink and support is provided by the supplier when required.

The cables have proven to be reliable to date and the maintenance activities are designed to prevent damage from human activity, erosion, vermin activity, and vegetation growth.

Fast and accurate voltage control by the converter stations as well fast runback functionality enable Murraylink to operate in a weak part of the Australian transmission network.

HVDC VSC Technology – Summary

The development of and applications for the HVDC VSC technology are rapidly evolving and widening. With it's inherent flexible features, e.g. for connection of renewable energy sources and the capability to provide "invisible transmission" via cable systems, there is no doubt it will be an important part of the modern transmission grid. More studies and benchmarking of the HVDC VSC operation performance, for different applications, will therefore be a vital measurement to further develop the technology. This paper has shown the performance of two existing installations.

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