

City centre in-feed feasible by HVDC Light[®]

Staffan Rudin, Guang Bai, Changchun Zhou

Power Technologies & Corporate Research
ABB (China) Limited

Introduction

As the size of a concentrated load in cities increases due to the on-going urbanization, metropolitan power networks have to be continuously upgraded to meet the demand. Environmental issues are also becoming more and more of a concern all over the world. Strong forces are pushing for replacing old local generation with power transmission from cleaner sources. This could for instance be long distance hydro-power. Land space being scarce and expensive, substantial difficulties arise whenever new right-of-way is to be secured for the feeding of additional power with traditional transmission lines. With increasing power levels, the risk of exceeding the short-circuit capability of existing switchgear equipment and other network components becomes another real threat to further expansion. Increasing demands on the power quality in urban areas is also a factor to consider for the power system engineer.

The HVDC Light[®] system is a solution to these problems. This technology is designed to transmit large quantities of power using underground cables and at the same time add stability and power quality to the connected networks. The cables are easily installed underground using existing right of ways, existing cable ducts, roads, subways, railways or channels. The HVDC Light[®] converter stations are compact and by virtue of their control, they do not contribute to the short-circuit levels.

As its name implies, HVDC Light[®] is a high voltage, direct current transmission technology and is well suited to meet the demands of competitive power market for transmission up to 1100 MW. In comparison traditional HVDC, or if you like HVDC Heavy, is designed for high voltage direct current transmission up to 3000MW.

HVDC Light[®] design is based on modular concept build up from standardized designs with compact transportable modules, which are factory assembled and pre-tested to provide short delivery and a fast response to the competitive market demands. These standardized modular designs allow for delivery times as short as 12 months.

General Comparison of HVDC Light[®] and HVDC Classic

HVDC Light[®] utilizes several important technological developments:

- High voltage valves with series-connected IGBTs
- Compact, dry, high-voltage dc capacitors
- High capacity control system
- Solid dielectric DC cable

Below is a brief summary of the main differences between HVDC Light[®] and conventional HVDC Classic:

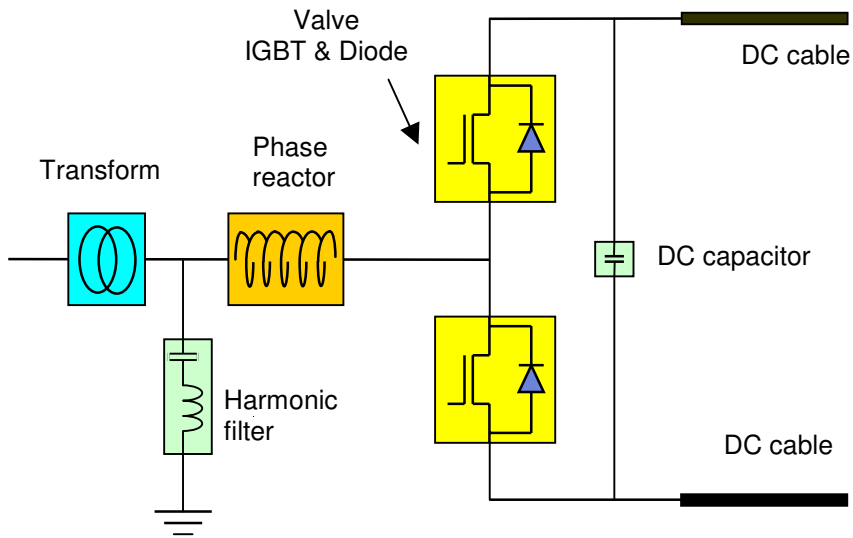


Figure 1. Simplified single-line diagram for HVDC Light[®]

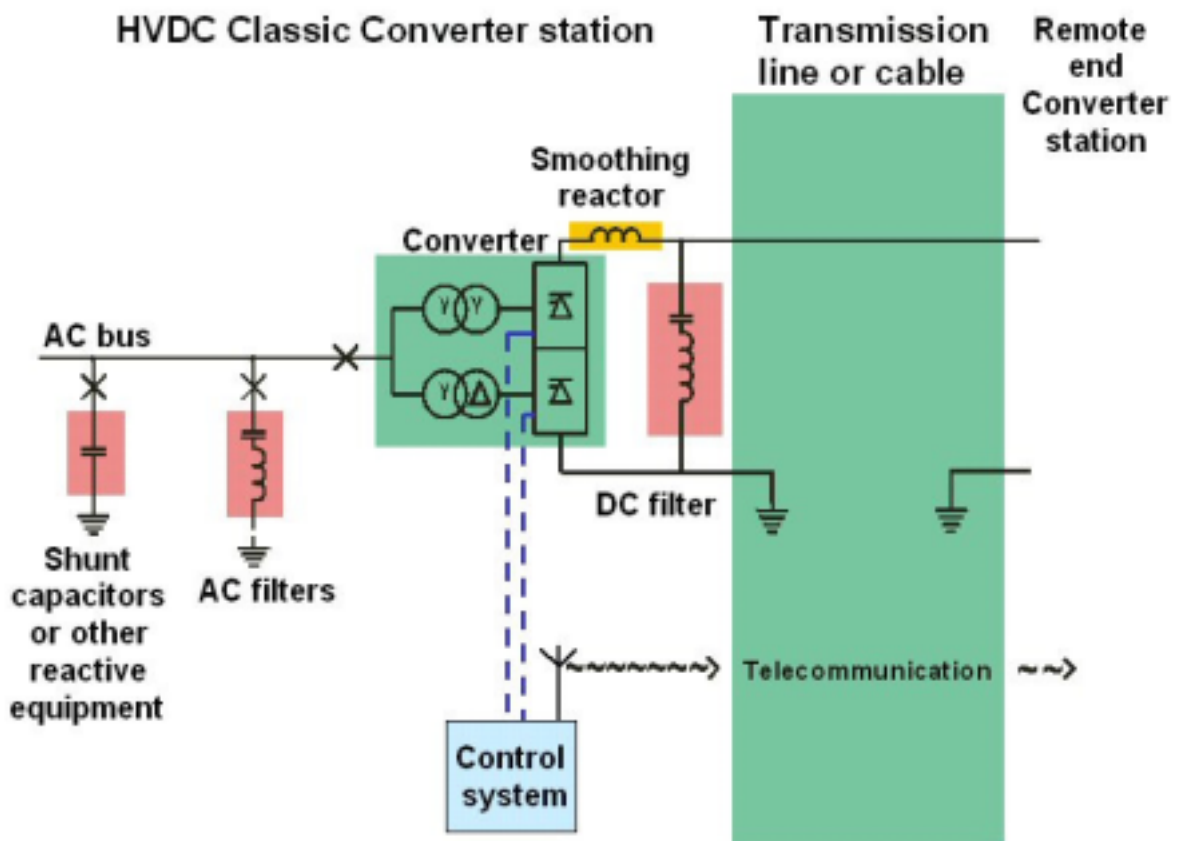




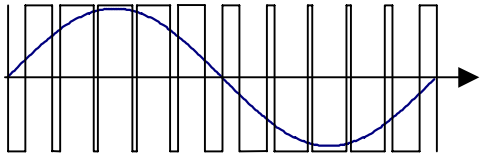


Figure 2. Simplified single-line diagram for conventional HVDC

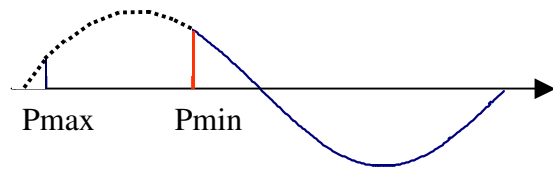
<p align="center">HVDC Light® power from 50 – 1100 MW</p>	<p align="center">Conventional HVDC, power up to 3000 MW</p>
	
<ul style="list-style-type: none"> - Each terminal is an HVDC converter plus an SVC - Suitable both for submarine and land cable connections - Advanced system features - Footprint (e.g. 550 MW): 120 x 50 x 11 meters - Short delivery time 	<ul style="list-style-type: none"> - Most economical way to transmit power over long distances. - Long submarine cable connections. - Around three times more power in a ROW than overhead AC - Footprint (e.g. 600 MW): 200 x 120 x 22 meters
<p>IGBT used as active component in valves</p>  <ul style="list-style-type: none"> - Multi-chip design - Forward blocking only - Current limiting characteristics - Gate turn-off and fully controllable; forced commutation - High-speed device 	<p>Thyristor used as active component in valves</p>  <ul style="list-style-type: none"> - Single silicon wafer - Both forward and reverse blocking capability - Very high surge current capability - No gate turn-off; line commutated

The pulse width controls both active and reactive power

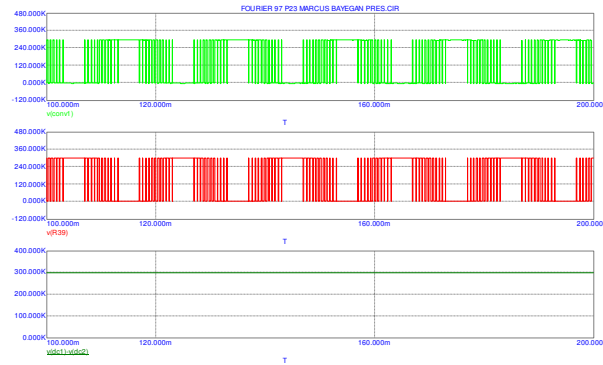


- The IGBT CAN be switched off with a control signal. Fully controllable.
= forced commutation up to 2000 Hz

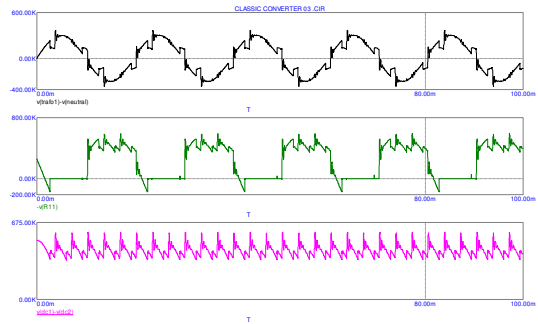
Phase angle control



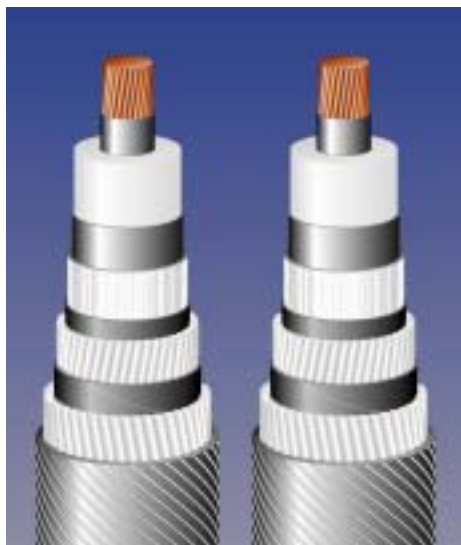
- The thyristor cannot be switched off with a control signal. It automatically ceases to conduct when the voltage reverses.
= line commutated, 50/60 Hz



- Upper trace: Reactor voltage
- Middle trace: Valve voltage
- Lower trace: DC Voltage



- Upper trace: Transformer voltage
- Middle trace: Valve voltage
- Lower trace: DC voltage



Extruded plastic cable



Mass impregnated oil cable

The HVDC Light[®] Converter Station

Depending on the converter rating, a number of series-connected IGBT valves are arranged in a two-level bridge. Each IGBT position is individually controlled and monitored via fiber optics. The semiconductor used in HVDC Light[®] is the StakPak[™] IGBT from ABB. The IGBT (insulated gate bipolar transistor) is a hybrid of the best of two worlds. As a conducting device, the bipolar transistor with its low forward voltage drop is used for handling high currents. Instead of the regular current-controlled base, the IGBT has a voltage-controlled capacitive gate, as in the MOSFET device. To increase the power handling, six IGBT chips and three diode chips are connected in parallel in a sub-module. A StakPak[™] IGBT has two, four or six sub-modules, which determine the current rating of the IGBT.



Figure 3. ABB StakPak[™] 4-sub and 6-sub IGBTs

Each VSC station is built up with modular valve housings which are constructed to shield electromagnetic interference (EMI). The valves are cooled with circulating water and water to air heat exchangers. PWM switching frequencies for the VSC typically range between 1-2 kHz depending on the converter topology, system frequency and specific application.

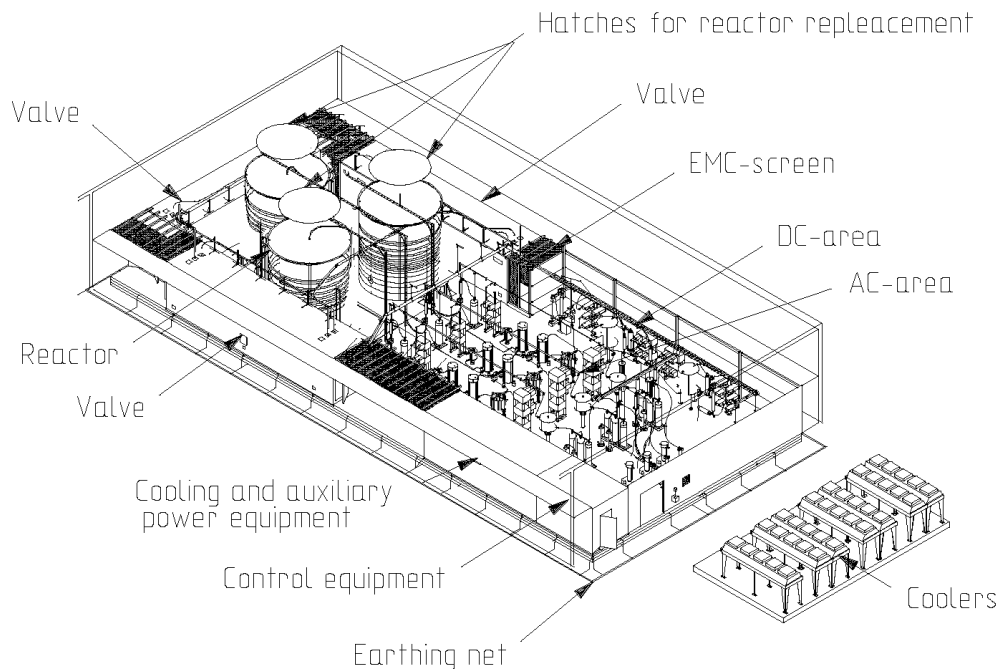


Figure 4. Typical HVDC Light[®] Station

Each VSC is effectively mid-point grounded and coupled to the AC bus via phase reactors and a power transformer with intermediary shunt AC filters. The AC filters are tuned to multiples of the switching frequency. This arrangement minimizes harmonic content and avoids dc voltage stresses in the transformer which allows use of a standard AC power transformer for matching the AC network voltage to the converter AC voltage necessary to produce the desired DC transmission voltage.

The HVDC Light[®] Cable

The HVDC Light[®] cable is a new design triple extruded, polymeric insulated DC-cable, which has been successfully type tested to 150kV DC, following a comprehensive R & D program. It is a new lightweight cable similar in appearance and characteristics to a standard AC, XLPE cable except that the problem associated with space charges which breakdown the insulation when using AC, XLPE cables on DC has been overcome with this new design.

The cables are operated in bipolar mode, one cable with positive polarity and one cable with negative polarity. The cables have polymeric insulating material, which is very strong and robust. This strength and flexibility make the HVDC Light[®] cables perfect for severe installation conditions:

- The land cables can be installed less costly with plowing technique.
- The submarine cables can be laid in deeper waters and on rough seabeds.
- HVDC cables can also be installed as overhead cables.

DC underground cables provide significant advantages, compared with overhead power lines. These include:

- Reduced environmental impact, an underground cable has no visual impact.
- Faster and easier issue of permits using DC underground cables.
- Virtually no magnetic radiation associated with the bi-polar DC cable.

Compared with AC underground cables the HVDC Light[®] cable also has some significant advantages to be considered:

- DC cables require only two cables between each converter station.
- DC-cables have no technical limit to distance.
- DC cables can carry up to 50% more power than the equivalent AC cable.

When considering the cost of installing an HVDC Light[®] underground transmission it is important to consider the total life cost benefits and not just the initial up front capital costs.

Power System Advantage

In an HVDC Light[®] system the active and reactive power can be controlled at the same time like in a synchronous converter, but the control is much faster, in the millisecond range. This fast control makes it possible to create any phase angle or amplitude, which can be done almost instantaneously providing independent control of both active and reactive power. From a system point of view it acts as a motor or a generator without mass.

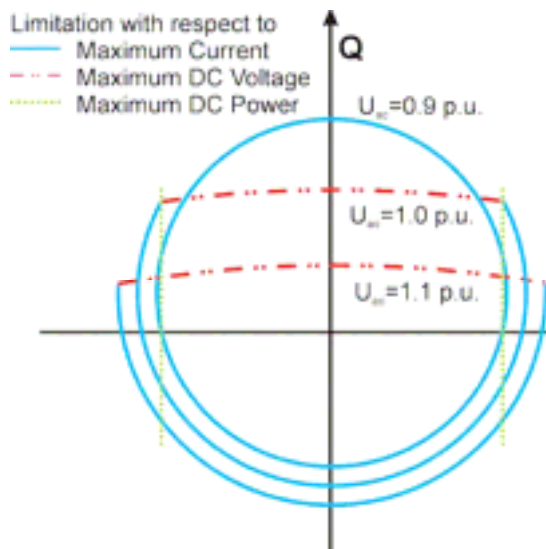


Figure 5. An HVDC Light[®] can control both active and reactive power (VSC Capability Curve)

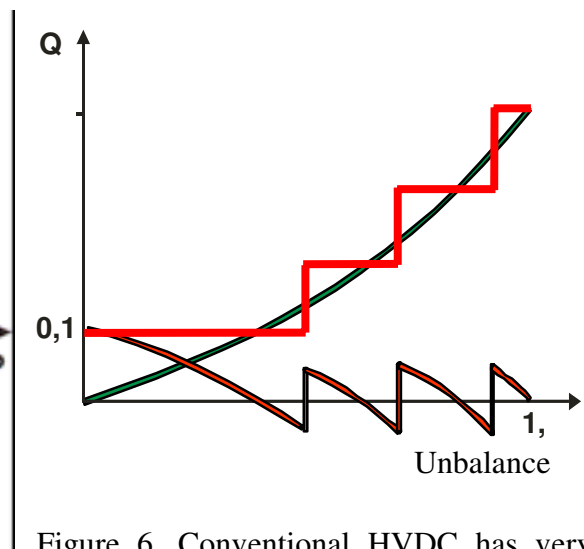


Figure 6. Conventional HVDC has very limited control of reactive power

There are mainly three factors that limit the capability curve (Fig 5) of an HVDC Light[®] transmission system seen from a power system stability perspective. The first one is the maximum current through the IGBT:s. This will give rise to a maximum MVA circle in the power plane where maximum current and actual AC voltage is multiplied. If the AC voltage decreases so will also the MVA capability. The second limit is the maximum DC voltage level. The reactive power is mainly dependent on the voltage difference between the AC voltage the VSC can generate from the DC voltage and the grid AC voltage. If the grid AC voltage is high the difference between the maximum DC voltage and the AC voltage will be low. The reactive power capability is then moderate but increases with decreasing AC voltage. This makes sense from a stability point of view. The third limit is the maximum DC current through the cable. For a decreasing AC voltage level the maximum DC voltage level will vanish and the maximum current level will decide the capability. Note the similarities with this capability curve and a capability curve for a generator. Maximum DC voltage level corresponds to maximum field current in the rotor winding and IGBT current corresponds to armature current.

An HVDC Light[®] system can virtually instantly take any working point within the capability chart. Instant active power flow reversals are also possible since the HVDC Light[®] system changes DC current direction and not DC voltage polarity. The XLPE-based cable technology used will handle such current reversals without any problem. Any limitations in the maximum power changing rates of the connecting AC grids must naturally be taken into account.

In a typical city infeed application the HVDC Light[®] system is connected in parallel to an AC connection. In this case the control of the HVDC Light[®] will have impact on the AC flow. By varying the power factor of the DC transmission we will be able to utilize the AC system better. In order to enhance system operation we must pick the best power factor operation for the HVDC Light[®] transmission when the system becomes stressed. Figure 7a)-b) shows a parallel case with the associated power circle plane. If we begin studying the receiving end circle we can see the power flow on the AC-line (following the arc with angle δ) to which the power flow via the HVDC Light[®] system is added (the vector within the smaller circle). In this example, the AC line is requiring some reactive power which is fed from the HVDC

Light[®] system. In the figure, the MVA circle (the small one) is valid for the HVDC Light[®] system. We see that the MVA capacity is at its maximum point for the DC system i.e. we can not transfer more power over the combination. An increase of DC flow or AC flow (requiring more reactive power to keep AC voltage) would violate the capability curve. If we now decrease DC power transfer and are able to inject more reactive power one can see that it is possible to transfer more active power over the combination. A best choice is made according to:

$$P_{dc} = I_{limit} \cdot V_2 \sin(\delta_1 - \delta_2) \quad \text{and} \quad Q_{dc} = I_{limit} \cdot V_2 \cos(\delta_1 - \delta_2)$$

where I_{limit} is the maximum steady state current allowed in the converter. If the maximum DC voltage level limit is included in the figure its role is directly disclosed in the drawing.

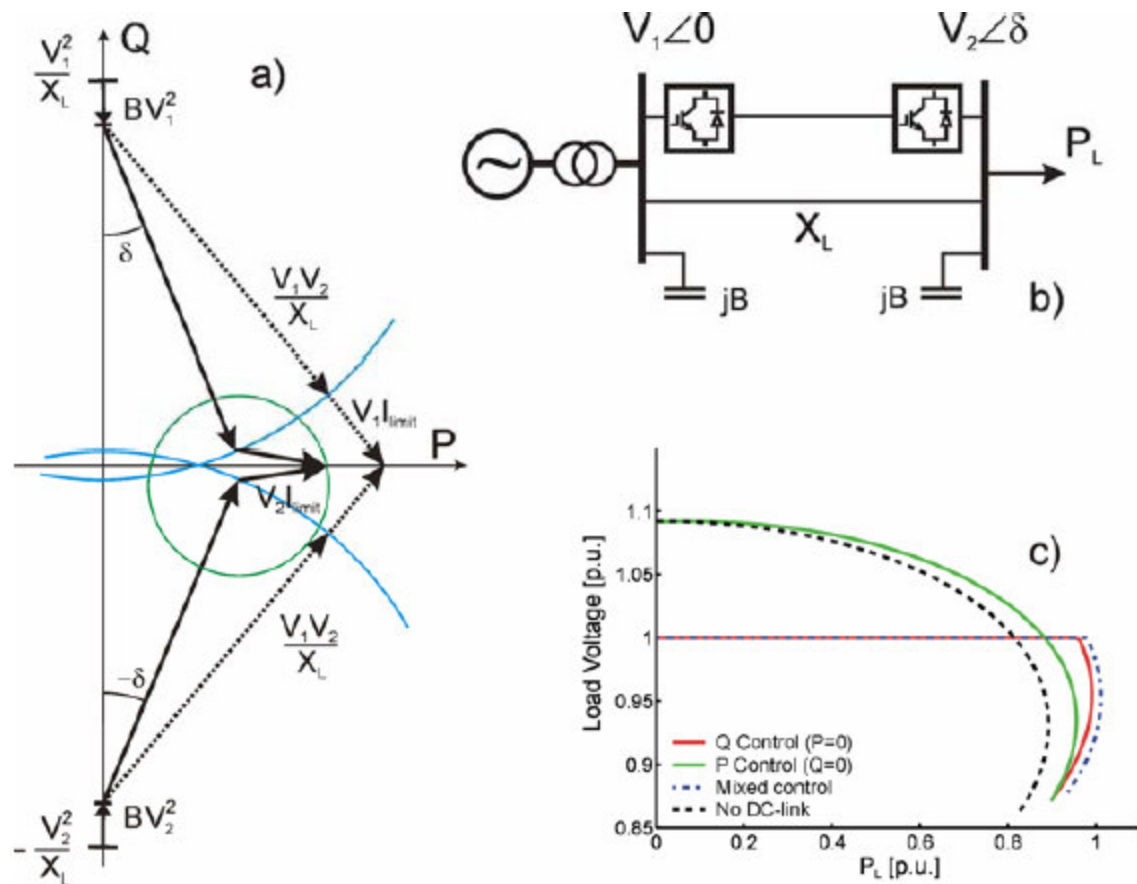


Figure 7 A parallel case b) with a power circle plane, a) to indicate 'best' solution. PV curve in c). Key grid parameters are $X_L=0.5$, $B=0.2$, ($SIL=0.872$ p.u.), $X_t=0.2$ p.u. and converter size=0.08 p.u.

The associated PV-curve is plotted in Figure 7c). It shows three different ways to utilize the capacity in the HVDC Light[®] system. The first one is active power transfer only, the second is only reactive power generation in each end (STATCOM operation) and the third one is a mixture according to the best choice described above. Point of Maximum Loadability, P_{max} for the three possibilities are indicated in Table I. The best choice in this example increases the point of maximum loadability with 149% of installed MVA capacity.

Table I Loadability as a function of different control strategies

Method	Pmax [p.u.]	Gain [p.u.]	Gain/Converter size
No DC	0.8923		
P Control	0.9561	0.0638	-20%
Q Control	0.9908	0.0985	+23%
Mixed Control	1.0117	0.1194	+49%

Emergency Power and Black Start Capability

A VSC transmission system will be a very valuable asset during a grid restoration. It will be available almost instantly after the blackout and does not need any short circuit capacity in order to become connected to the grid. The benefits will differ if one or both ends are exposed to the blackout. The following list highlights some aspects:

- No need for short circuit power for commutation. Black start capability if equipped with a small diesel generator feeding auxiliary power (or power from another grid).
- Fast voltage control is available in both ends virtually instantly after the auxiliary power is back.
- Can energize a few transmission lines at a lower voltage level avoiding severe Ferranti-overvoltage and allow remote end connection of transformers/reactors at a safer voltage level.
- When the remote end is connected to the reactor/transformer the voltage can be ramped up to its nominal value.
- When active power is available in the remote end the VSC connection can feed auxiliary power to local plants making sure that they have a stable voltage/frequency to start on.
- When the local plants are synchronized to the grid they can ramp up power production at a constant and safe speed and do not initially have to participate in frequency control. Thermal time constants and control issues in the boiler can then be handled. The VSC transmission system is taking care of frequency variations via power exchange to the remote grid. This will increase the likelihood of a successful startup. Islanding operation of a single power plant is seldom tested beforehand and the operation is therefore not reliable. The VSC transmission system does not have thermal/mechanical systems that are affected by rapidly changing active power demand and will therefore be a safer and tested way to use for frequency control. It can also temporarily export power from the island meaning that we can have a considerable overproduction available in the island before we start to connect load.
- When the power production margins are safe we can start connecting load. The system is now ready to handle phenomena as cold load pickup and varying AC voltage in the transmission grid. More generation is fed with auxiliary power and then connected.
- Classic HVDC can be started when the short circuit capacity is sufficient.

The buildup scheme has the potential of being quite robust and fast especially if the remote VSC system end is connected to a strong grid. Speed and robustness during the buildup should be very valuable since the consequences in the society significantly differ if the blackout is 15 minutes or 6 hours.

An example - Cross Sound HVDC Light®

The Cross Sound Cable (CSC) provides a directly controllable merchant interconnection between the New England and Long Island systems in parallel to the congested New York City transmission network.



Figure 8. The Cross Sound Cable feeding Long Island, New York

The interconnection is rated 330MW, ± 150 kV. The 40 km submarine cable is buried on the sea bottom. The Cross Sound Cable increases regional reliability by increasing the ability of the New England and New York networks to share generating capacity. It can also reduce the overall cost of power to consumers as well as reduce overall CO₂ emissions by allowing the shared use of more efficient generation units. The attributes of HVDC Light® transmission simplify system operation and the interconnection's interface with each regional system.

The two HVDC Light® power cables and the multi fiber optic cable were laid bundled together to minimize the impact on the seabed and to protect oysters, scallops and other living species. The cables were buried six feet into the sea floor to give protection against fishing gear and ships' anchors.



Figure 9. HVDC Light® station at New Haven

Testing of the Cross Sound Cable project was completed in August 2002. The big blackout in the north-eastern states happened on August 14, 2003. During the blackout the Cross Sound transmission became an important power supply route to Long Island when restoring the network during the blackout. Some hours after the blackout, a federal order was given to start emergency operation. CSC was the first transmission link to Long Island that was put into

service after the blackout. In addition to providing power to Long Island, the AC voltage control provided by the link of both Long Island and Connecticut networks showed that it could keep the AC voltages constant during system faults. Thunderstorms that occurred before the networks were completely restored forced the CSC to several +100 to -70 Mvar swings over 20 seconds. The AC voltage was kept constant. The owner has concluded that the cable interconnection was a great part of the success of getting Long Island out of the dark, and restoring power. Millions of consumers in the New York area benefited from the quick network rebound.

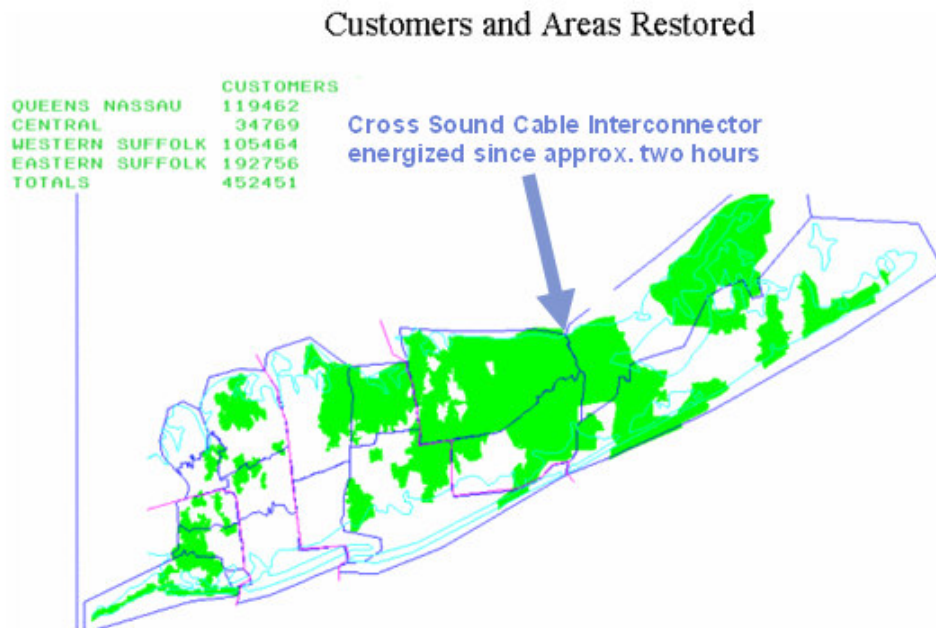


Figure 10. Actual power restoration build up from HVDC Light[®] converter station

After start of commercial operation the Cross Sound Cable has shown a consistent availability (scheduled and forced) of 98 %.

CONCLUSIONS

HVDC Light[®] is a power system designed to transmit power underground and underwater. It offers numerous environmental benefits, such as no overhead lines, neutral electromagnetic fields, oil-free cables and compact converter stations. These benefits make new transmission projects in densely populated areas acceptable for the public.

For the power system engineer the HVDC Light[®] technology offers a number of additional benefits such as:

- Independent active/reactive power control
- Black start capability
- Power stability benefits

An example from real life has shown that the HVDC Light[®] system worked as planned during a blackout situation and was a key factor for fast system restoration.

BIOGRAPHY

Staffan Rudin (1965) has a Master Degree in Electrical Engineering from the Institute of Technology Lund, Sweden. Mr. Rudin has 15 years of experience in the Power T&D area. This includes development and design of both FACTS and HVDC systems. Mr Rudin previously held a position as Manager of the ABB FACTS System Design group in Sweden. His current position at ABB is Marketing Manager HVDC Light[®] & FACTS in China.

Guang Bai has a Master's degree in Power System Reliability and a Bachelor's degree in Power System Automation. He has six years working experience with Northeast China Power Design Institute. He joined ABB China in 2003 and now is working with the Power Grid business.

Changchun Zhou got his Ph.D degree in Electrical Engineering from Zhejiang University, China. His research areas focus on HVDC and FACTS modeling and analysis. Mr Zhou joined ABB Corporate Research in 2004 as a Senior Research Engineer, now he is working on HVDC Light[®] modeling.

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