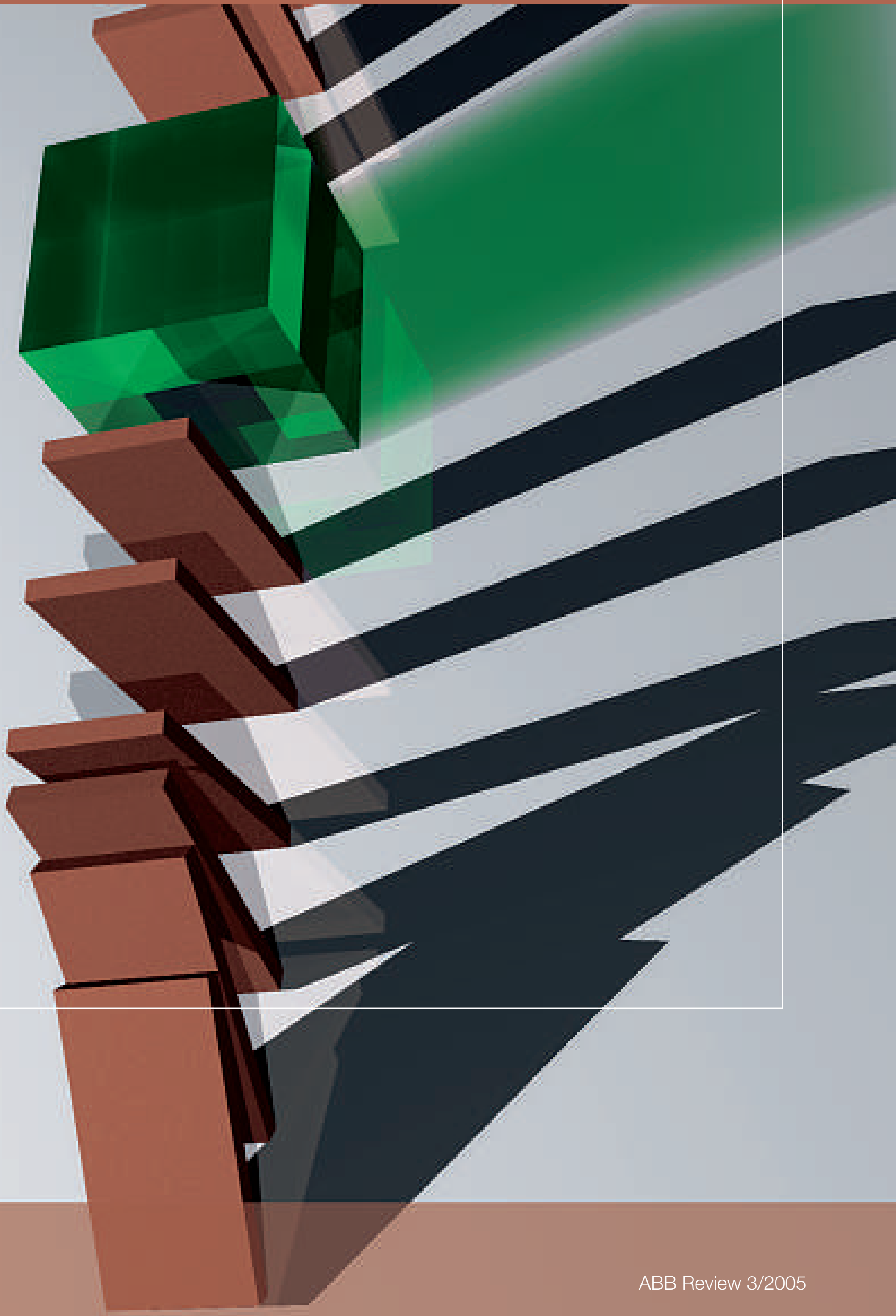
HVDC

A “firewall” against disturbances in high-voltage grids

Lennart Carlsson

Interconnections between grids are desirable because they not only permit economies through the sharing of reserves, but they also make the trading of electricity between grids possible. On the downside, however, disturbances can easily spread from one area to another. Major blackouts in recent years have shown how relatively minor malfunctions can have repercussions over wider areas. As one link overloads it is tripped, increasing the strain on neighboring links which in turn disconnect, cascading blackouts over vast areas and causing huge productivity losses for the economy.

The solution is a “firewall” permitting the interchange of power but preventing the spread of disturbances. This can be accomplished using high voltage DC (HVDC) connections. A HVDC link can fully control transmission but does not overload or propagate fault currents.



The severe cascading blackouts that have been seen in many parts of the world highlight the vulnerability of large AC systems. Investment in transmission facilities has been marginal in North America and Europe for the last 20–30 years despite rising demand and generation. This reluctance was largely due to public opposition to new transmission lines and to unclear regulations on how compensation for these links should be distributed to grid owners or investors in the freshly deregulated market.

Interconnections allow power consumers to benefit from generation at the site of lowest incremental cost. At the same time they permit the sharing of reserves, spinning and otherwise. But interconnections also provide doorways for the propagation of disturbances.

The more complex the mesh of system interconnections, the more difficult it is to control. Outages that may at first seem of little importance can cascade into large areas.

HVDC transmissions make an important contribution to controlling power transmissions, safeguarding stability and containing disturbances.

Since 1999, the power systems expert, George C. Loehr (see textbox) has been advocating the breaking up of the two gigantic interconnections or grids that straddle North America into a number of smaller ones1). These mini-grids can be interconnected with HVDC lines instead of the present AC ties. Loehr explains, "with AC, what happens in one place on the grid affects everywhere else. A major disturbance in Ontario is felt as far away as Oklahoma, Florida and Maine. This doesn't happen with DC – it insulates one small grid from the others, but still permits power exchange."

Because of this inherent control capability, HVDC links do not become overloaded; they act as a "firewall" containing the disturbance.

HVDC and HVDC Light® – fundamental system characteristics

In an HVDC transmission 1, 2, electric power is taken from a three-phase AC network, converted to DC in a converter station, transmitted to the receiving point by a cable or overhead line and then converted back to AC in another converter station and injected into the receiving AC network. As the conversion process is fully controlled, the transmitted power is not dictated by impedances or phase angle differences as is the case with AC. In classical HVDC, which has been on the market for 50 years [1], thyristor valves perform the AC/DC conversion. Typically, the rated power of an HVDC transmission is more than 100 MW; many are in the 1,000–3,000 MW range.

On an HVDC system, the power flow is controlled rapidly and accurately. Both the power level and the direction are determined by control systems. This improves the dispatch freedom as well as the performance and efficiency of the connected AC networks.

In HVDC Light®, the newly developed IGBT-valves replace thyristors. These not only carry out the AC/DC conversion but add new features and flexibility. It is a fundamentally new transmission technology developed by ABB in the 1990s. It is particularly suitable for small-scale power transmission applications (presently up to 550 MW) and extends the economical power range of HVDC transmissions down to just a few tens of MW. HVDC Light® 3 [2] is sometimes called "The invisible power transmission" as it uses underground cables.

Some HVDC applications

Classical HVDC is frequently used to interconnect separate power systems where traditional AC connections cannot be used: eg, 50/60 Hz system interfaces or where independent frequency control of the separate networks exists. Such connections are sometimes realized as "back to back" systems, ie, rectifier (AC to DC station) and inverter (DC to AC station) are located at the same site.

Many long distance HVDC transmissions (> 600 km) connect generation sites (large hydro and thermal stations) to optimum injection points in the network.

HVDC cable transmissions are mostly of submarine type (> 50 km) and often link asynchronous power systems.

HVDC Light® units of up to 350 MW are now in full commercial operation while units up to 550 MW have been developed. The link between the converter stations is by oil-free extruded cables (land and/or submarine) presently up to 180 km [3]. HVDC Light® can also be implemented back-to-back.

Power control

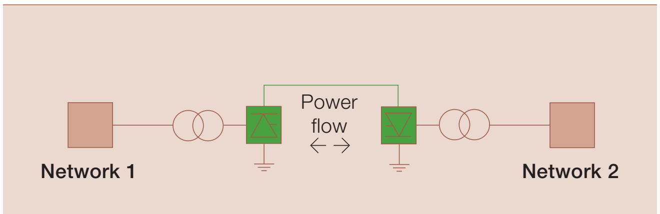
Classical thyristor based HVDC transmission can vary the power level

George C. Loehr

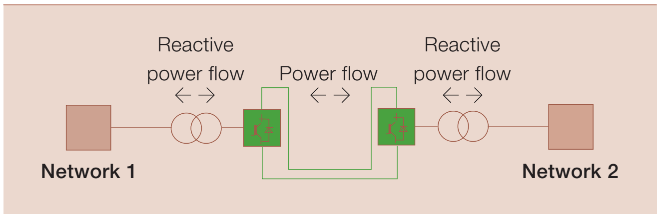
George C. Loehr is a recognized national expert on electric power system reliability, with more than 40 years in the field. He frequently serves as an expert witness, consultant, teacher, writer and lecturer on electric power subjects. His articles have appeared frequently in trade magazines [6], and he is coeditor of and a contributor to the IEEE book, The Evolution of Electric Power Transmission Under Deregulation: Selected Readings.

George C. Loehr has a degree from Manhattan College and an M.A. degree in English literature from New York University. He is the former Executive Director of the Northeast Power Coordinating Council and currently serves as Vice President on the Board of Directors of the American Education Institute.

1 Classic HVDC base scheme for interconnection.



2 HVDC Light base scheme for interconnection.



from minimum load (normally between 5 and 10 percent) to max load (100 percent). Below minimum load, the transmission can be put in hot standby. Operator initiated changes are performed according to a predefined ramp rate. Changes in power direction can be made in standby and can take effect in a fraction of a second.

HVDC Light® does not have a minimum power level. It is able to vary power from + 100 percent to – 100 percent progressively, without interruption, and without switching filter or shunt banks.

Performance under AC system faults

When a temporary fault occurs in the AC system connected to the rectifier, the HVDC transmission may suffer a power loss. Even in the case of close single-phase faults, the link may transmit up to 30 percent of the pre-fault power. As soon as the fault is cleared, power is restored to the pre-fault value.

When a temporary fault occurs in the AC system connected to the inverter, a commutation failure can occur interrupting power flow. Power is restored as soon as the fault is cleared. A distant fault with little effect on the converter station voltage (less than ≈ 10 percent) does not normally lead to a commutation failure. A CCC (Capacitor Commutated Converter) HVDC converter [4] can tolerate about twice this voltage drop before there is a risk of commutation failure.

HVDC Light® is even more fault-tolerant. Since the converter can control the reactive power and the filters are small, the loss of active power has no impact on the AC voltage.

Another advantage of both HVDC and HVDC Light® transmissions is that they do not contribute to the fault current: the impact on the fault-free side of the DC transmission is smaller, and on the side with the fault, the fault current is lower than it would be with an AC link. The fault-free network experiences an interruption of power flow in the DC transmission but no fault current.

How HVDC can help during contingencies

The major cascading blackouts were all initiated by relatively minor local events or a combination of such events.

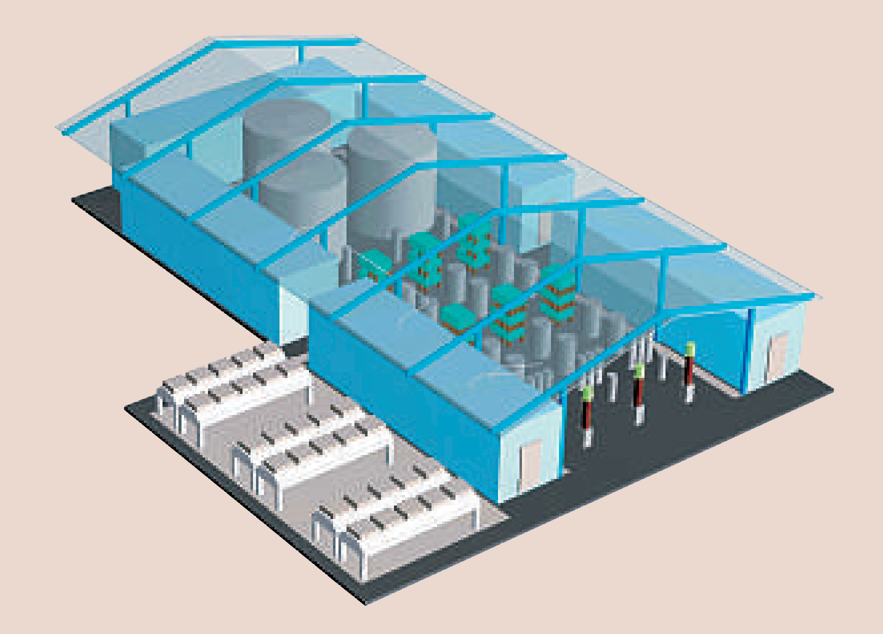
In most cases, these lead to a voltage collapse. Often the main reason why the fault condition *spreads* to a wide area is that AC transmission links became overloaded. This leads to their disconnection which in turn overloads other lines and so on.

An HVDC transmission link is easily engineered to take specific remedial actions in case of a disturbance. Furthermore, such actions are often smooth and continuous – in contrast to the hard switching of AC links.

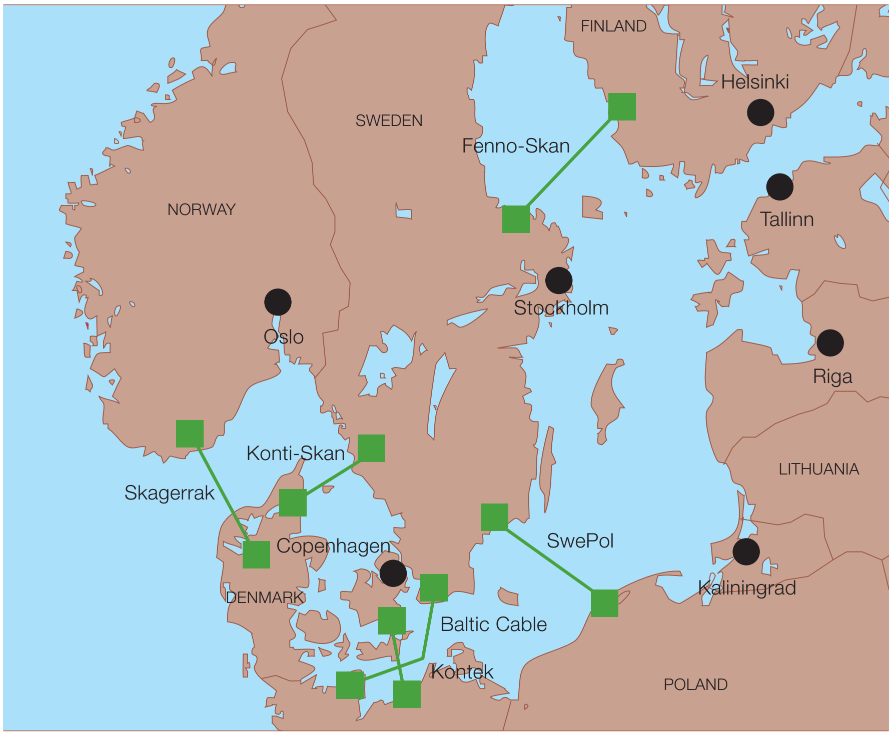
Normal power control

The most important feature of HVDC is that it can *never* become overloaded! The transmitted power in HVDC is defined by its control; it is not dictated by the phase angle differences between its terminals. There are of course circumstances that can cause

3 HVDC Light Converter station.



4 All of these six Scandinavian HVDC links, with a combined rating of 4,000 MW, are provided with emergency power control.

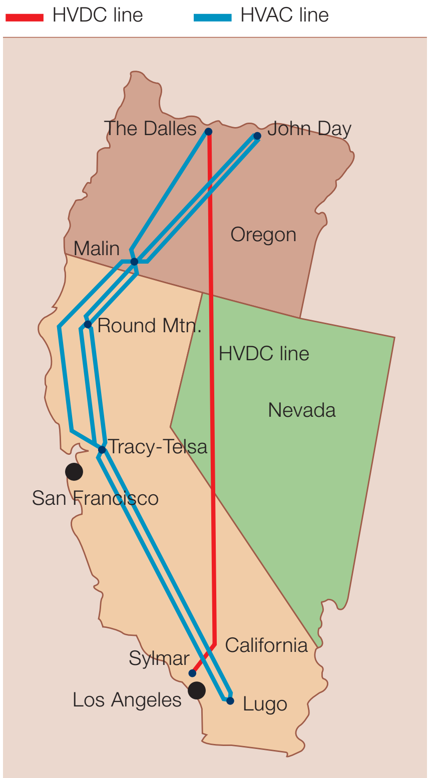


power transmission to cease in a DC link, such as lack of power in the sending end, a severe voltage collapse in one of the networks, or a sudden fault in the DC transmission itself. But in the majority of disturbances in the AC system, the power from the DC transmission link can be relied on.

Emergency power control

When a DC transmission connects two asynchronous networks and there is, a sudden outage of generation in one of the networks leading to an abnormal frequency and/or voltage, the link can be made to automatically adapt its power flow to support the troubled grid. The power flow is limited so as not to jeopardize the integrity of the sending network.

5 The Pacific Northwest-Southwest Intertie.



When a DC transmission is connected inside an AC-grid with AC lines parallel to the DC-link, the power in these lines can be monitored and the DC power can be automatically adapted to protect the AC lines from being overloaded.

Voltage control

In a disturbed network, voltage depressions or oscillations often occur. In many cases the reactive power capability of a classical HVDC station can help reduce this by connecting capacitors and/or by modulating the station's reactive power consumption by firing angle control. An HVDC Light® converter has an even greater ability to generate or consume reactive power within a wide range by very rapid control action.

Application examples

There are many examples of how DC transmissions have helped prevent outages or helped in limiting the consequences of major disturbances. Three examples from Europe and the USA are discussed. The power rating of all three HVDC links has been upgraded since these events.

- On April 10, 1979 the ELSAM Network in western Denmark was islanded together with parts of the German network. The load on the island was 5,000 MW and production 3,850 MW. Within 3 seconds, the frequency fell to 48.1 Hz. Part of the load was shed by under-frequency protection. The Skagerrak (500 MW) and Konti-Skan (250 MW) HVDC links from Norway and Sweden remained in service 4. Skagerrak automatically increased power from 50 to 320 MW and Konti-Skan from 0 to 125 MW within 3 seconds. The frequency was quickly restored to normal and a blackout prevented.
- On another occasion the Scandinavian network experienced a frequency drop to 48.5 Hz when two 1000 MW nuclear stations in Sweden were disconnected. The same two HVDC links intervened. The Skagerrak link was at the time exporting its rated power (500 MW) from Norway to Denmark. When the frequency drop occurred, the power direction reversed and 500 MW were injected into the Norwegian/Swedish grid (a net contribution of 1000 MW).
- The Pacific HVDC Intertie runs between Oregon and Los Angeles in the Western USA. It is parallel to a number of 500 kV AC lines 5. On December 22 1982 there was a loss of two AC lines north of the Tesla substation due to high winds. This resulted in the overloading of other AC lines, and finally in the splitting of the WSCC$^{2)}$ system into four major islands. More than 12,000 MW of load were shed and 5.2 million customers had their service interrupted.
- The Pacific HVDC Intertie was the only transmission to the Southern California island that remained in service during this disturbance. It limited the extent of system outages and provided valuable generating support to the Southern California and Southern Nevada areas.

Further differences between HVDC Classic and HVDC Light®

Dependence on Short Circuit Power from the connected AC grid

Classical, thyristor based, HVDC depends on the correct functioning of the AC system. The AC/DC converter requires a minimum Short Circuit Power$^{3)}$ (S_{SC}) from the connected AC

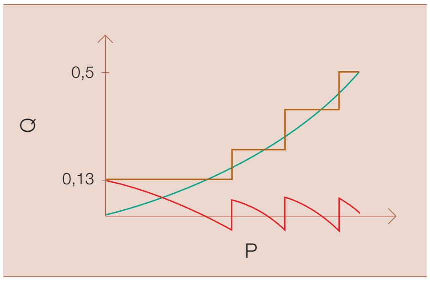
The 2,000 MW Sandy Pond HVDC station outside Boston is the receiving station of hydropower from Hydro Quebec.

The Shoreham station of the 330 MW HVDC Light Cross Sound Cable link between Connecticut and Long Island, USA.

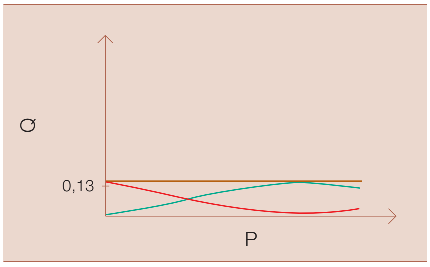
6 Reactive power in conventional HVDC and CCC HVDC as function of the active power.

🟧 Filter 🟩 Converter 🟥 Imbalance

a) Conventional



b) CCC



grid. Classical HVDC cannot feed power into a network which lacks generation completely or which has little or very remote generation. A common measure of the adequacy of this is the so-called Short Circuit Ratio (SCR) that relates the Short Circuit Power (S_{SC}) to the Rated Power (P_{DC}) of the HVDC transmission:

$$SCR=\frac{S_{SC}}{P_{DC}}$$

For correct functioning, this ratio should be at least 2.5–3.0. Special measures can reduce this threshold further. One very effective measure developed by ABB is the so-called CCC (Capacitor-Commutated Converter) [4], allowing the SCR to be reduced to 1.0 or less.

HVDC Light® does not rely on short circuit power to function because the inverter does not require the help of external generators. It can thus energize a "dead" network.

Reactive power

A great advantage of HVDC is that it does not transmit reactive power.

The classical HVDC converter consumes reactive power; it is therefore common practice to include a reactive power supply in the converter station. This is normally done in harmonic filters and shunt capacitor banks. These resources are switched in steps by circuit breakers depending on the transmitted power and the needs of the AC network 6a.

The CCC HVDC converter consumes less reactive power as the converter includes a series capacitor 6b. A classical thyristor based HVDC station can participate in stabilizing the AC voltage by modulating its reactive power consumption by firing angle control, and by switching filters and shunt banks.

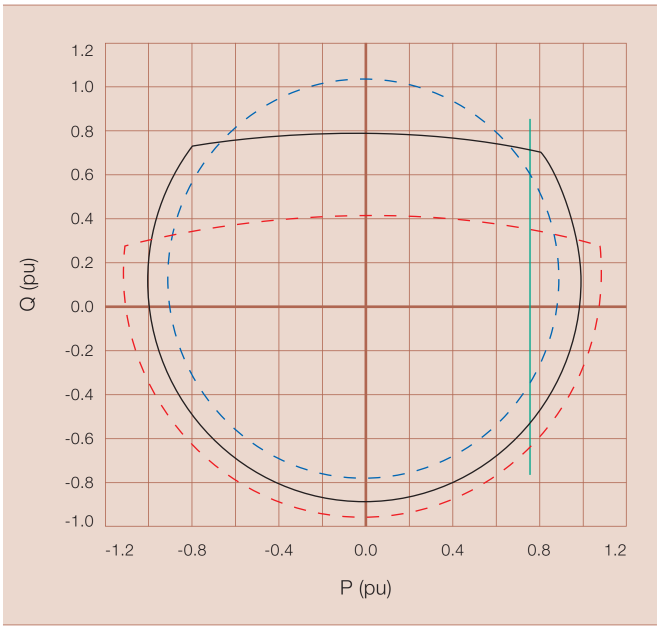
An HVDC Light® converter has the ability to generate or consume reactive power within a wide range by control of the IGBT valves without switching filters or shunt banks. HVDC Light® can thus take an even more prominent roll in stabilizing the AC voltage 7.

Summary

Power grid system planners and transmission owners should consider HVDC when planning investment in today's ageing transmission system. Besides their inherent suitability for very long lines and submarine cables, HVDC offers additional benefits through its ability to control power flow.

7 Operation capability of an HVDC Light® converter.

🟥 U=1.1 pu ⬛ U=1 pu 🟦 U=0.9 pu 🟩 P desired



Limiting the size of synchronous AC-grids and interconnecting them with HVDC will combine the economical benefits of interconnection with HVDC "firewall" functionality, preventing or limiting the cascading of disturbances. Relieving heavily loaded AC corridors is another HVDC contribution to system security.

According to Harrison K. Clark [5]: "Segmentation with HVDC can improve reliability while increasing transfer capability by limiting the propagation of disturbances. Seeing the benefits to segmentation requires thinking outside the box."

Read more about HVDC and HVDC Light on www.abb.com/hvdc.

Lennart Carlsson
ABB Power Technologies AB
Power Systems
Ludvika, Sweden
lennart.k.carlsson@se.abb.com

Footnotes

[1] In an interview after the blackout in the northeastern USA and Canada on 14th August 2003.

[2] Western System Coordinating Council: a system of lines interconnecting the western USA, Canada and Mexico.

[3] Short Circuit Power is the product of the hypothetical short circuit current and the nominal voltage. It increases with generation power and decreases with the impedance between generator and short circuit.

References

[1] Asplund G., Carlsson L., Tollerz O., "50 years HVDC", parts 1 & 2, ABB Review 4/2003.

[2] Asplund G., Eriksson K., Svensson, K., "Transmission based on Voltage Source Converter" CIGRE SC14 Colloquium in South Africa, 1997.

[3] Wyckmans, M., "HVDC Light, the new technology" Distribution 2003, Adelaide, Australia, 2003.

[4] Jonsson T., Björklund, P-E: "Capacitor Commutated Converters for HVDC", IEEE Power Tech Conference, Stockholm, 1995.

[5] Clark, Harrison K., "It's Time to Challenge Conventional Wisdom", Transmission & Distribution, Oct. 2004.

[6] Loehr, George C., "Is it Time to Cut the Ties that Bind?", Transmission & Distribution World, March 2004.