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HIGH VOLTAGE DC TRANSMISSION

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***Abstract*-High voltage DC (HVDC) transmission systems are designed to interface with the AC network in such a way as to have considerable operating flexibility and minimal harmonic impact. Filter design as well as gating controls are designed at the inverter with the stated objective in view. Sometimes designs and operating regimes are an engineering compromise relating to the amplitude of several harmonic voltages and currents, inverter performance at the power frequency, operational power level, SCR or valve parameters (eg. margin angle), and equipment requirements. The harmonic impact of an inverter is considered in this paper with regard to network harmonic response. An analysis procedure based on the harmonic power flow algorithm is described and required models, points of modeling questions, shortcomings, and advantages of the procedure are described. The procedure is illustrated for a twelve pulse, bipolar HVDC inverter with high pass, 11th, and 13th harmonic filters on the AC bus. The general approach, and modelling details are verified by measurements on the Square Butte HVDC system. Tests were performed at and near the Arrowhead terminal of this system (operated as an inverter); measurement of harmonics in bus voltage, line current, and currents in shunt capacitors were made. Also, certain converter currents and parameters were recorded. Since the objective was to verify network response, some measurements were made in the AC network remote to the HVDC inverter.**

I. INTRODUCTION

A high-voltage, direct current (HVDC) electric power transmission system uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating current (AC) systems. For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses. For underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle. For shorter distances, the higher cost of DC conversion equipment compared to an AC system may still be warranted, due to other benefits of direct current links.

HVDC allows power transmission between unsynchronized AC transmission systems. Since the power flow through an HVDC link can be controlled independently of the phase angle between source and load, it can stabilize a network against disturbances due to rapid changes in power. HVDC also allows transfer of power between grid systems running at different frequencies, such as 50 Hz and 60 Hz. This improves the stability and economy of each grid, by allowing exchange of power between incompatible networks.

II. HIGH VOLTAGE TRANSMISSION

High voltage is used for electric power transmission to reduce the energy lost in the resistance of the wires. For a given quantity of power transmitted, doubling the voltage will deliver the same power at only half the current. Since the power lost as heat in the wires is proportional to the square of the current for a given conductor size, but does not depend on the voltage, doubling the voltage reduces the line losses per unit of electrical power delivered by a factor of 4. While power lost in transmission can also be reduced by increasing the conductor size, larger conductors are heavier and more expensive.

High voltage cannot readily be used for lighting or motors, so transmission-level voltages must be reduced for end-use equipment. Transformers are used to change the voltage levels in alternating current (AC) transmission circuits. AC became dominant after the War of Currents competition between the direct current (DC) system of Thomas Edison and the AC system of George Westinghouse because transformers made voltage changes practical, and AC generators were more efficient than those using DC.

Practical conversion of power between AC and DC became possible with the development of power electronics devices such as mercury-arc valves and, starting in the 1970s, semiconductor devices as thyristors, integrated gate-commutated thyristors (IGCTs), MOS-controlled thyristors (MCTs) and insulated-gate bipolar transistors (IGBT).

III. HISTORY OF HIGH VOLTAGE DC TRANSMISSION

The first long-distance transmission of electric power was demonstrated using direct current in 1882 at Miesbach-Munich Power Transmission, but only 1.5 kW was transmitted. An early method of high-voltage DC transmission was developed by the Swiss engineerRené Thury and his method was put into practice by 1889 in Italy by the Acquedotto De Ferrari-Gallier company. This system used series-connected motor-generator sets to increase the voltage. Each set was insulated from electrical ground and driven by insulated shafts from a prime mover. The transmission line was operated in a 'constant current' mode, with up to 5,000 volts across each machine, some machines having double commutators to reduce the voltage on each commutator. This system transmitted 630 kW at 14 kV DC over a distance of 120 km. The Moutiers–Lyon system transmitted 8,600 kW of hydroelectric power a distance of 200 km, including 10 km of underground cable. This system used eight series-connected generators with dual commutators for a total voltage of 150,000 volts between the positive and negative poles, and operated from c.1906 until 1936. Fifteen Thury systems were in operation by 1913. Other Thury systems operating at up to 100 kV DC worked into the 1930s, but the rotating machinery required high maintenance and had high energy loss. Various other electromechanical devices were tested during the first half of the 20th century with little commercial success.

IV. MERCURY ARC VALVES

Mercury arc valves require an external circuit to force the current to zero and thus turn off the valve. In HVDC applications, the AC power system itself provides the means of *commutating* the current to another valve in the converter. Consequently, converters built with mercury arc valves are known as line-commutated converters (LCC). LCCs require rotating synchronous machines in the AC systems to which they are connected, making power transmission into a passive load impossible.

V. THYRISTOR VALVES

HVDC systems have used only solid-state devices, in most cases thyristor valves. Like mercury arc valves, thyristors require connection to an external AC circuit in HVDC applications to turn them on and off. HVDC using thyristor valves is also known as line-commutated converter (LCC) HVDC.

VI. CAPACITOR-COMMUTATED CONVERTER

Line-commutated converters have some limitations in their use for HVDC systems. This results from requiring the AC circuit to turn off the thyristor current and the need for a short period of 'reverse' voltage to effect the turn-off (turn-off time). An attempt to address these limitations is the Capacitor-Commutated Converter *(*CCC*)* which has been used in a small number of HVDC systems. The CCC differs from a conventional HVDC system in that it has series capacitors inserted into the AC line connections, either on the primary or secondary side of the converter transformer. The series capacitors partially offset the *commutating inductance* of the converter and help to reduce fault currents. This also allows a smaller *extinction angle* to be used with a converter/inverter, reducing the need for reactive power support. However, CCC has remained only a niche application because of the advent of voltage-source converters (VSC) which completely eliminate the need for an extinction (turn-off) time.

VII. VOLTAGE SOURCE CONVERTERS

Widely used in motor drives since the 1980s, voltage-source converters started to appear in HVDC in 1997 with the experimental Hellsjön–Grängesberg project in Sweden. By the end of 2011, this technology had captured a significant proportion of the HVDC market. The development of higher rated insulated-gate bipolar transistors (IGBTs), gate turn-off thyristors (GTOs) and integrated gate-commutated thyristors (IGCTs), has made smaller HVDC systems economical. The manufacturer ABB Group calls this concept HVDC *Light*, while Siemens calls a similar concept HVDC *PLUS* (Power *Link* Universal System) and Alstom call their product based upon this technology HVDC MaxSine. They have extended the use of HVDC down to blocks as small as a few tens of megawatts and lines as short as a few score kilometres of overhead line. There are several different variants of VSC technology: most installations built until 2012 use pulse width modulation in a circuit that is effectively an ultra-high-voltage motor drive. Current installations, including HVDC PLUS and HVDC MaxSine, are based on variants of a converter called a Modular Multi-Level Converter (MMC).

VIII. ADVANTAGES OF HIGH VOLTAGE DC OVER AC

The most common reason for choosing HVDC over AC transmission is that HVDC is more economic than AC for transmitting large amounts of power point-to-point over long distances. A long distance, high power HVDC transmission scheme generally has lower capital costs and lower losses than an AC transmission link.

Even though HVDC conversion equipment at the terminal stations is costly, overall savings in capital cost may arise because of significantly reduced transmission line costs over long distance routes. HVDC needs fewer conductors than an AC line, as there is no need to support three phases.

Depending on voltage level and construction details, HVDC transmission losses are quoted as about 3.5% per 1,000 km, which is less than typical losses in an AC transmission system.

HVDC transmission may also be selected because of other technical benefits that it provides for the power system. HVDC schemes can transfer power between separate AC networks. HVDC powerflow between separate AC systems can be automatically controlled to provide support for either network during transient conditions, but without the risk that a major power system collapse in one network will lead to a collapse in the second.

The combined economic and technical benefits of HVDC transmission can make it a suitable choice for connecting energy sources that are located far away from the main load centers.

Specific applications where HVDC transmission technology provides benefits include:

- Undersea cables transmission schemes (e.g., 250 km Baltic cables between Sweden and Germany. the 580 km NorNed cable between Norway and the Netherlands, and 290 km Basslink between the Australian mainland and Tasmania).
- Endpoint-to-endpoint long-haul bulk power transmission without intermediate 'taps', usually to connect a remote generating plant to the main grid, for example the Nelson River DC Transmission System in Canada.
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install.
- Power transmission and stabilization between unsynchronised AC networks, with the extreme example being an ability to transfer power between countries that use AC at different frequencies. Since such transfer can occur in either direction, it increases the stability of both networks by allowing them to draw on each other in emergencies and failures.
- Stabilizing a predominantly AC power-grid, without increasing fault levels (prospective short circuit current).

IX. DISADVANTAGES

The disadvantages of HVDC are in conversion, switching, control, availability and maintenance.

HVDC is less reliable and has lower availability than alternating current (AC) systems, mainly due to the extra conversion equipment. Single-pole systems have availability of about 98.5%, with about a third of the downtime unscheduled due to faults. Fault-tolerant bipole systems provide high availability for 50% of the link capacity, but availability of the full capacity is about 97% to 98%.

The required converter stations are expensive and have limited overload capacity. At smaller transmission distances, the losses in the converter stations may be bigger than in an AC transmission line for the same distance. The cost of the converters may not be offset by reductions in line construction cost and lower line loss.

Operating a HVDC scheme requires many spare parts to be kept, often exclusively for one system, as HVDC systems are less standardized than AC systems and technology changes faster.

In contrast to AC systems, realizing multiterminal systems is complex (especially with line commutated converters), as is expanding existing schemes to multiterminal systems. Controlling power flow in a multiterminal DC system requires good communication between all the terminals; power flow must be actively regulated by the converter control system instead of the inherent impedance and phase angle properties of the transmission line. Multi-terminal systems are rare. As of 2012 only two are in service: the Hydro Québec – New England transmission between Radisson, Sandy Pond and Nicolet and the Sardinia–mainland Italy link which was modified in 1989 to also provide power to the island of Corsica.

HVDC circuit breakers are difficult to build because some mechanism must be included in the circuit breaker to force current to zero, otherwise arcing and contact wear would be too great to allow reliable switching. In November 2012, ABB announced development of the world's first HVDC circuit breaker.

The ABB breaker contains four switching elements, two mechanical (one high-speed and one low-speed) and two semiconductor (one high-voltage and one low-voltage). Normally, power flows through the low-speed mechanical switch, the high-speed mechanical switch and the low-voltage semiconductor switch. The last two switches are paralleled by the high-voltage semiconductor switch.

Initially, all switches are closed (on). Because the high-voltage semiconductor switch has much greater resistance than the mechanical switch plus the low-voltage semiconductor switch, current flow through it is low. To disconnect, first the low-voltage semiconductor switch opens. This diverts the current through the high-voltage semiconductor switch. Because of its relatively high resistance, it begins heating very rapidly. Then the high-speed mechanical switch is opened. Unlike the low-voltage semiconductor switch, which is only capable of standing off the voltage drop of the closed high-voltage semiconductor switch, this is capable of standing off the full voltage. Because no current is flowing through this switch when it opens, it is not damaged by arcing. Then, the high-voltage semiconductor switch is opened. This actually cuts the power. However, it only cuts power to a very low level; it is not quite 100% off. A final low-speed mechanical switch disconnects the residual current.

X. COST OF HIGH VOLTAGE DC TRANSMISSION

Generally, providers of HVDC systems, such as Alstom, Siemens and ABB, do not specify cost details of particular projects. It may be considered a commercial matter between the provider and the client.

Costs vary widely depending on the specifics of the project (such as power rating, circuit length, overhead vs. cabled route, land costs, and AC network improvements required at either terminal). A detailed comparison of DC vs. AC transmission costs may be required in situations where there is no clear technical advantage to DC alone, and economical reasoning drives the selection.

However, some practitioners have provided some information:

For an 8 GW 40 km link laid under the English Channel, the following are approximate primary equipment costs for a 2000 MW 500 kV bipolar conventional HVDC link (exclude way-leaving, on-shore reinforcement works, consenting, engineering, insurance, etc.)

- Converter stations ~£110M (~€120M or $173.7M)
- Subsea cable + installation ~£1M/km (~€1.2M or ~$1.6M/km)

So for an 8 GW capacity between England and France in four links, little is left over from £750M for the installed works. Add another £200–300M for the other works depending on additional onshore works required.

An April 2010 announcement for a 2,000 MW, 64 km line between Spain and France is estimated at €700 million. This includes the cost of a tunnel through the Pyrenees.