HVDC Transmission Overview

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Abstract – **High Voltage Direct Current (HVDC) technology has characteristics which make it especially attractive in certain transmission applications. The number of HVDC projects committed or under consideration globally has increased in recent years reflecting a renewed interest in this field proven technology. New HVDC converter designs and improvements in conventional HVDC design have contributed to this trend. This paper provides an overview of the rationale for selection of HVDC technology and describes some of the latest technical developments.**

Keywords – **Cable - HVDC – IGBT Valves - Thyristor Valves – Transmission – Voltage-Sourced Converters**

I. Introduction

High Voltage Direct Current (HVDC) technology has characteristics which makes it especially attractive for certain transmission applications. HVDC transmission is widely recognized as being advantageous for long-distance, bulk-power delivery, asynchronous interconnections and long submarine cable crossings. The number of HVDC projects committed or under consideration globally has increased in recent years reflecting a renewed interest in this mature technology. New converter designs have broadened the potential range of HVDC transmission to include applications for underground, offshore, economic replacement of reliability-must-run generation, and voltage stabilization. Developments include higher transmission voltages up to ± 800 kV, capacitor-commutated converters (CCC) for weak system applications and voltage-sourced converters (VSC) with dynamic reactive power control. This broader technology range has increased the potential HVDC applications and contributed to the recent growth of HVDC transmission. Fig. 1 shows the Danish terminal for Skagerrak pole 3 rated 440 MW. Fig. 2 shows the ± 500 kV HVDC transmission line for the 2000 MW Intermountain Power Project between Utah and California.

II. HVDC Applications

HVDC transmission applications can be broken down into different basic categories. Although the rationale for selection of HVDC is often economic, there may be other reasons for its selection. HVDC may be the only feasible way to interconnect two asynchronous networks, reduce fault currents, utilize long cable circuits, bypass network congestion, share utility rights-of-way without degradation of reliability and to mitigate environmental concerns. In all of these applications, HVDC nicely complements the ac transmission system.

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Fig. 1. HVDC converter station with AC filters in the foreground and valve hall in the background

Fig. 2. ± 500 kV HVDC transmission line

A. *Long Distance Bulk Power Transmission*

HVDC transmission systems often provide a more economical alternative to ac transmission for long-distance, bulk-power delivery from remote resources such as hydro-electric developments, mine-mouth power plants or large-scale wind farms. Higher power transfers are possible over longer distances using fewer lines with HVDC transmission than with ac transmission. Typical HVDC lines utilize a bipolar configuration with two independent poles. Bipolar HVDC lines are comparable to a double circuit ac line since they can operate at half power with one pole out of service but require only one-third the insulated sets of conductors as a

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double circuit ac line. The controllability of HVDC links offers firm transmission capacity without limitation due to network congestion or loop flow on parallel paths. Controllability allows the HVDC to 'leap-frog' multiple 'choke-points' or bypass sequential path limits in the ac network. Therefore, the utilization of HVDC links is usually higher than that for EHV ac transmission lowering the transmission cost per MWh. This controllability can also be very beneficial for the parallel transmission as well since, by eliminating loop flow, it frees up this transmission capacity for its intended purpose of serving intermediate load and providing an outlet for local generation.

Whenever long distance transmission is discussed, the concept of "break-even distance" frequently arises. This is where the savings in line costs offsets the higher converter station costs. A bipolar HVDC line uses only two insulated sets of conductors rather than three. This results in narrower ROW, smaller transmission towers and lower line losses than with ac lines of comparable capacity. A rough approximation of the savings in line construction is 30%. Although break-even distance is influenced by the costs of right-of-way and line construction with a typical value of 500 km, the concept itself is misleading because in many cases more ac lines are needed to deliver the same power over the same distance due to system stability limitations. Furthermore, the long distance ac lines usually require intermediate switching stations and reactive power compensation. This can increase the substation costs for ac transmission to the point where it is comparable to that for HVDC transmission.

For example, the generator outlet transmission alternative for the ± 250 kV, 500 MW Square Butte Project was two 345 kV series-compensated ac transmission lines. The 12,600 MW, Itaipu project has half its power delivered on three 800 kV series-compensated ac lines (three circuits) and the other half delivered on two ± 600 kV bipolar HVDC lines (four circuits). Similarly, the ± 500 kV, 1600 MW Intermountain Power Project (IPP) ac alternative comprised two 500 kV ac lines. The IPP Project takes advantage of the double circuit nature of the bipolar line and includes a 100% short-term and 50% continuous monopolar overload. The first 6000 MW stage of the transmission for the Three Gorges Project in China would have required 5 x 500 kV ac lines as opposed to 2 x ± 500 kV, 3000 MW bipolar HVDC lines.

Table 1 contains an economic comparison of capital costs and losses for different ac and dc transmission alternatives for a hypothetical 750 mile, 3000 MW transmission system. The long transmission distance requires intermediate substations or switching stations and shunt reactors for the ac alternatives. The long distance and heavy power transfer, nearly twice surge-impedance loading on the 500 kV ac alternatives, require a high level of series compensation. These ac station costs are included in the cost estimates for the ac alternatives.

Most long distance HVDC transmission systems with power levels above 1000 MW are at a bipolar voltage level of ±500 kV. The 2 x 3150 MW Itaipu HVDC transmission system in Brazil has been operating at ±600 kV since the mid 1980's. Transmission voltages of ±600 kV to ±800 kV are classified as UHVDC. Higher power transfers can be achieved over longer distances with lower losses by increasing the dc voltage level into the UHVDC range. A considerable body of work is ongoing in this area for potential applications in China, India and North America. The controllability and the mechanical and electrical characteristics of UHVDC lines make them in many respects more favorable for long distance bulk power transmission than UHVAC lines.

B. Cable Transmission

Unlike the case for ac cables, there is no physical restriction limiting the distance or power level for HVDC underground or submarine cables. Underground cables can be used on shared ROW with other utilities without impacting reliability concerns over use of common corridors. For underground or submarine cable systems there is considerable savings in installed cable costs and cost of losses when using HVDC transmission. Depending on the power level to be transmitted, these savings can offset the higher converter station costs at distances of 40 km or more. Furthermore, there is a drop-off in cable capacity with ac transmission over a distance due to its reactive component of charging current since cables have higher capacitances and lower inductances than ac overhead lines. Although this can be compensated by intermediate shunt compensation for underground cables at increased expense, it is not practical to do so for submarine cables.

With a cable system, the need to balance unequal loadings or the risk of post-contingency overloads often necessitates use of a series-connected reactors or phase shifting transformers. These potential problems do not exist with a controlled HVDC cable system.

Extruded HVDC cables with pre-fabricated molded joints used with VSC based HVDC transmission are lighter, more flexible and easier to splice than the mass-impregnated (MI), oil-paper cables used for conventional HVDC transmission thus making them more conducive for land cable applications where transport limitations and extra splicing costs can drive up installation costs. The lower cost cable installations made possible by the extruded HVDC cables and prefabricated joints makes long distance underground transmission economically feasible for use in areas with rights-of-way constraints or subject to permitting difficulties or delays with overhead lines.

C. Asynchronous Ties

With HVDC transmission systems, interconnections can be made between asynchronous networks for more economic or reliable system operation. The asynchronous interconnection allows interconnections of mutual benefit while providing a buffer between the two systems. Often these interconnections use back-to-back converters with no transmission line. Asynchronous HVDC links act as an effective "firewall" against propagation of cascading outages in one network from passing to another network.

Many asynchronous interconnections exist in North America between the eastern and western interconnected systems, between the Electric Reliability Council of Texas

(ERCOT) and its neighbors, e.g., Mexico and the Southwest Power Pool (SPP), and between Quebec and its neighbors, e.g., New England and the Maritimes. The August 2003 northeast blackout provides an example of the "firewall" against cascading outages provided by asynchronous interconnections. As the outage expanded and propagated around the lower Great Lakes and through Ontario and New York it stopped at the asynchronous interface with Quebec. Quebec was unaffected, the weak ac interconnections between New York and New England tripped, but the HVDC links from Quebec continued to deliver power to New England.

Regulators try to eliminate 'seams' in electrical networks because of their potential restriction on power markets. Electrical 'seams', however, serve as natural points of separation by acting as 'shear-pins' thereby reducing the impact of large-scale system disturbances. Asynchronous ties can eliminate market 'seams' while retaining natural points of separation.

Interconnections between asynchronous networks are often at the periphery of the respective systems where the networks tend to be weak relative to the desired power transfer. Higher power transfers can be achieved with improved voltage stability in weak system applications using capacitor commutated converters. The dynamic voltage support and improved voltage stability offered by VSC based converters permits even higher power transfers without as much need for ac system reinforcement. VSC converters do not suffer commutation failures allowing fast recoveries from nearby ac faults. Economic power schedules which reverse power direction can be made without any restrictions since there is no minimum power or current restrictions.

D. Offshore Transmission

Self-commutation, dynamic voltage control and black-start capability allow compact VSC HVDC transmission to serve isolated loads on islands or offshore production platforms over long distance submarine cables. This capability can eliminate the need for running expensive local generation or provide an outlet for offshore generation such as that from wind. The VSC converters can operate at variable frequency to more efficiently drive large compressor or pumping loads using high voltage motors.

Large remote wind generation arrays require a collector system, reactive power support and outlet transmission. Transmission for wind generation must often traverse scenic or environmentally sensitive areas or bodies of water. Many of the better wind sites with higher capacity factors are located offshore. VSC based HVDC transmission not only allows efficient use of long distance land or submarine cables but also provides reactive support to the wind generation complex and interconnection point.

E. Power Delivery to Large Urban Areas

Power supply for large cities depends on local generation and power import capability. Local generation is often older and less efficient than newer units located remotely. Often, however, the older, less-efficient units located near the city center must be dispatched out-of-merit because they must be run for voltage support or reliability due to inadequate transmission. Air quality regulations may limit the availability of these units. New transmission into large cities is difficult to site due to right of way limitations and land use constraints.

Compact VSC-based underground transmission circuits can be placed on existing dual-use rights-of-way to bring in power as well as to provide voltage support allowing a more economical power supply without compromising reliability. The receiving terminal acts like a virtual generator delivering power and supplying voltage regulation and dynamic reactive power reserve. Stations are compact and housed mainly indoors making siting in urban areas somewhat easier. Furthermore, the dynamic voltage support offered by the VSC can often increase the capability of the adjacent ac transmission.

III. SYSTEM CONFIGURATIONS

Fig. 3 shows the different common system configurations and operating modes used for HVDC transmission. The most common configuration for modern overhead HVDC transmission lines is bipolar with a single 12-pulse converter for each pole at each terminal. This gives two independent dc circuits each capable of half capacity. For normal balanced operation there is no earth current. Monopolar operation, often with overload capacity, can be used during outages of the opposite pole. Emergency earth return operation can be minimized during monopolar outages by using the opposite pole line for metallic return via pole/ converter bypass switches at each end. This not only is effective during converter outages but also during line insulation failures where the remaining insulation strength is adequate to withstand the low resistive voltage drop in the metallic return path. For very high power HVDC transmission especially at dc voltages above ± 500 kV, i.e., ± 600 kV or ± 800 kV, series-connected converters can be used to reduce the energy unavailability for individual converter outages or partial line insulation failure.

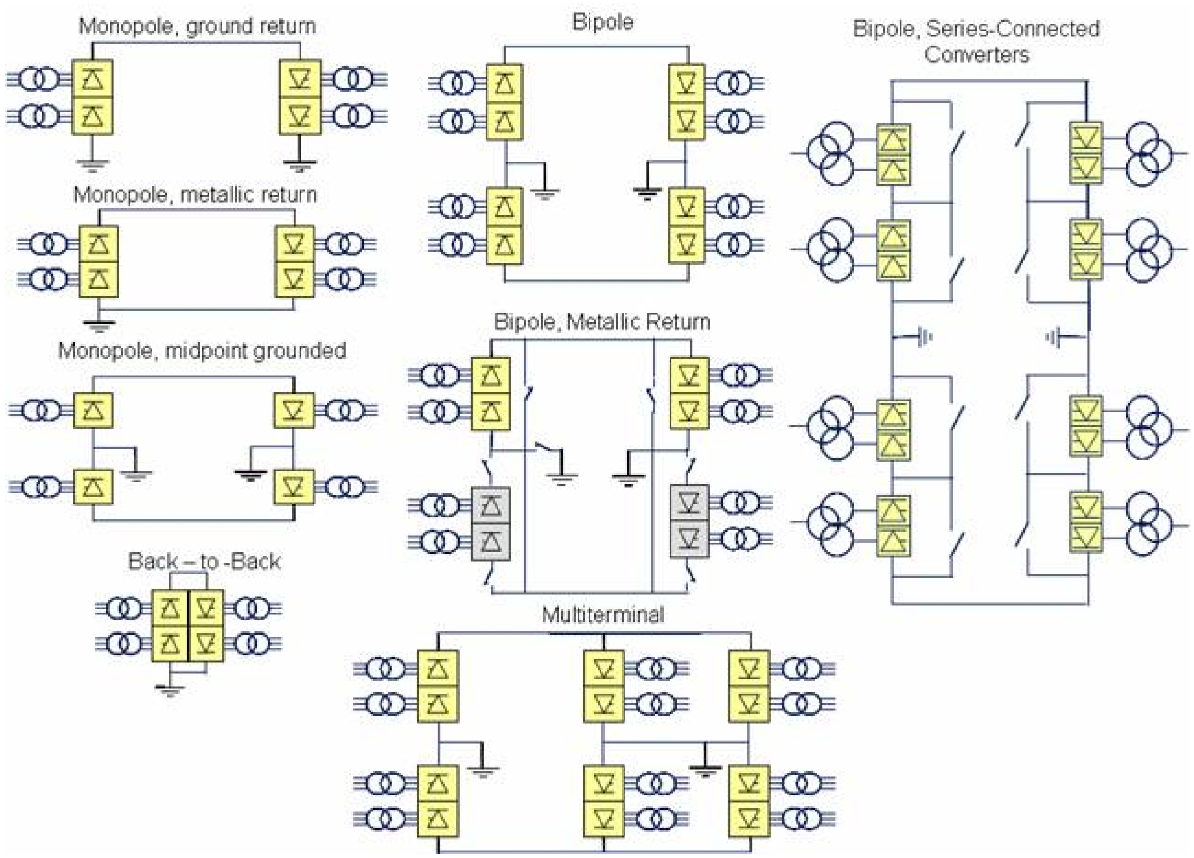

Fig. 3. HVDC configurations and operating modes

Comparative Costs of 3000 MW Transmission Systems

Alternative	DC Alternatives				AC Alternatives			Hybrid AC/DC Alternative		
	± 500 kV Bipole	**2 x ± 500 kV 2 Bipoles**	**± 600 kV Bipole**	**± 800 kV Bipole**	**500 kV 2 Single Ckt**	**500 kV Double Ckt**	**765 kV 2 Single Ckt**	**± 500 kV Bipole**	**500 kV Single Ckt**	**Total AC+DC**
Capital Cost										
Rated Power (MW)	3000	4000	3000	3000	3000	3000	3000	3000	1500	4500
Station costs including reactive compenstation	$420	$680	$465	$510	$542	$542	$630	$420	$302	$722
Transmission line cost (M$/mile)	$1.60	$1.60	$1.80	$1.95	$2.00	$3.20	$2.80	$1.60	$2.00	
Distance in miles	750	1,500	750	750	1,500	750	1,500	750	750	1,500
Transmission Line Cost (M$)	$1,200	$2,400	$1,350	$1,463	$3,000	$2,400	$4,200	$1,200	$1,500	$2,700
Total Cost (M$)	**$1,620**	**$3,080**	**$1,815**	**$1,973**	**$3,542**	**$2,942**	**$4,830**	**$1,620**	**$1,802**	**$3,422**
Annual Payment, 30 years @10%	$172	$327	$193	$209	$376	$312	$512	$172	$191	$363
Cost per kW-Yr	$57.28	$81.68	$64.18	$69.75	$125.24	$104.03	$170.77	$57.28	$127.40	$80.66
Cost per MWh @ 85% Utilization Factor	$7.69	$10.97	$8.62	$9.37	$16.82	$13.97	$22.93	$7.69	$17.11	$10.83
Losses @ full load	193	134	148	103	208	208	139	106	48	154
Losses at full load in %	6.44%	3.35%	4.93%	3.43%	6.93%	6.93%	4.62%	5.29%	4.79%	5.12%
Capitalized cost of losses @ $1500 kW (M$)	$246	$171	$188	$131	$265	$265	$177	$135	$61	$196

Parameters:

Interest rate %	10%
Capitalized cost of losses $/kW	$1,500

Note:
AC current assumes 94% pf
Full load converter station losses = 0.75% per station
Total substation losses (transformers, reactors) assumed = 0.5% of rated power

Table 1. Comparative Costs of HVDC and EHV AC Transmission Alternatives

IV. CORE HVDC TECHNOLOGIES

Two basic converter technologies are used in modern HVDC transmission systems. These are conventional line-commutated, current source converters (CSC) and self-commutated, voltage-sourced converters (VSC). Fig. 4 shows a conventional HVDC converter station with current source converters while Fig. 5 shows a HVDC converter station with voltage source converters.

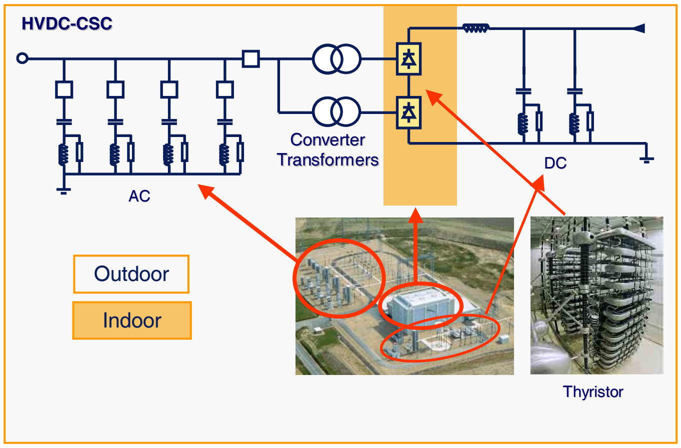

Fig. 4. Conventional HVDC with current source converters

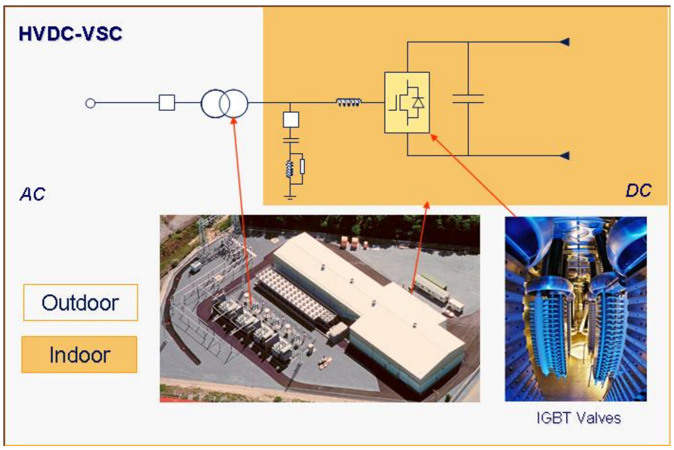

Fig. 5. HVDC with voltage source converters

A. Line-Commutated, Current-Sourced Converter

Conventional HVDC transmission employs line-commutated, current-source converters (CSC) with thyristor valves. Such converters require a synchronous voltage source in order to operate. The basic building block used for HVDC conversion is the three-phase, full-wave bridge referred to as a 6-pulse or Graetz bridge. The term 6-pulse is due to six commutations or switching operations per period resulting in a characteristic harmonic ripple of 6 times the fundamental frequency in the dc output voltage. Each 6-pulse bridge is comprised of 6 controlled switching elements or thyristor valves. Each valve is comprised of a suitable number of series-connected thyristors to achieve the desired dc voltage rating.

The dc terminals of two 6-pulse bridges with ac voltage sources phase displaced by 30 degrees can be connected in series to increase the dc voltage and eliminate some of the characteristic ac current and dc voltage harmonics. Operation in this manner is referred to as 12-pulse operation. In 12-pulse operation the characteristic ac current and dc voltage harmonics have frequencies of $12n \pm 1$ and $12n$ respectively. The 30 degree phase displacement is achieved by feeding one bridge through a transformer with a wye-connected secondary and the other bridge through a transformer with a delta connected secondary. Most modern HVDC transmission schemes utilize 12-pulse converters to reduce the harmonic filtering requirements required for 6-pulse operation, e.g., 5^{th} and 7^{th} on the ac side and 6^{th} on the dc side. This is because, although these harmonic currents still flow through the valves and the transformer windings, they are 180 degrees out of phase and cancel out on the primary side of the converter transformer. Fig. 6 shows the thyristor valve arrangement for a 12 pulse converter with three quadruple valves, one for each phase. Each thyristor valve is built up with series-connected thyristor modules.

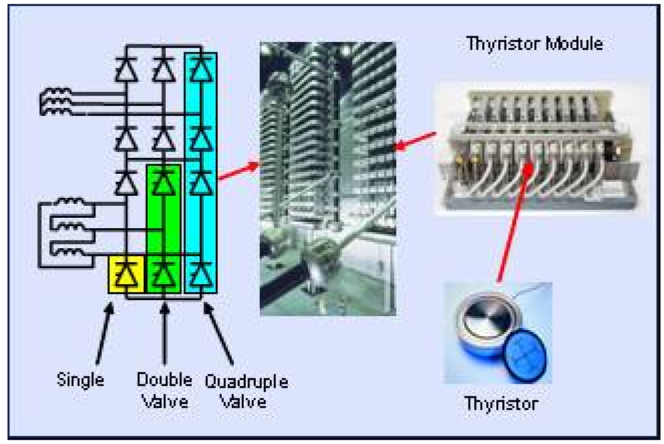

Fig. 6. HVDC thyristor valve arrangement

Line-commutated converters require a relatively strong synchronous voltage source in order to commutate. Commutation is the transfer of current from one phase to another in a synchronized firing sequence of the thyristor valves. The three phase symmetrical short circuit capacity available from the network at the converter connection point should be at least twice the converter rating for converter operation. Line-commutated current source converters can only operate with the ac current lagging the voltage so the conversion process demands reactive power.

B. Self-Commutated Voltage-Sourced Converter

HVDC transmission with VSC converters can be beneficial to overall system performance. VSC converter technology can rapidly control both active and reactive power independently of one another. Reactive power can also be controlled at each terminal independent of the dc transmission voltage level. This control capability gives total flexibility to place converters anywhere in the AC network since there is no restriction on minimum network short circuit capacity. Self commutation with VSC even permits black start, i.e., the converter can be used to synthesize a balanced set of three phase voltages like a virtual synchronous generator. The dynamic support of the ac voltage at each converter terminal improves the voltage stability and can increase the transfer capability of the sending and receiving end AC systems thereby leveraging the transfer capability of the DC link. Fig. 7 shows the IGBT converter valve arrangement for a voltage source converter station.

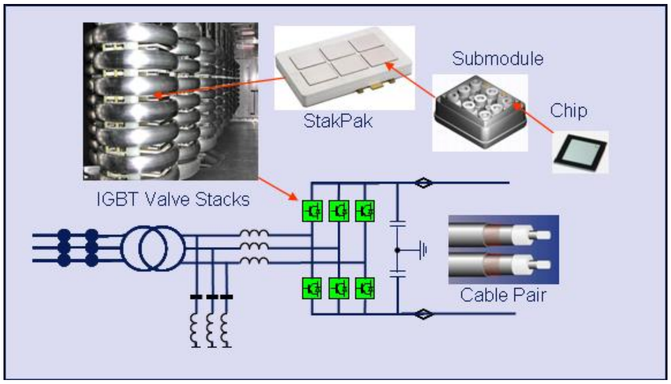

Fig. 7. HVDC IGBT valve arrangement

Reactive power demand of conventional HVDC is supplied from the ac filters which look capacitive at the fundamental frequency, shunt banks, or series capacitors which are an integral part of the converter station. Any surplus or deficit in reactive power from these local sources must be accommodated by the ac system. This difference in reactive power needs to be kept within a given band to keep the ac voltage within the desired tolerance. The weaker the ac system or the further the converter is away from generation, the tighter the reactive power exchange must be to stay within the desired voltage tolerance. Fig. 8 illustrates the reactive power demand, reactive power compensation and reactive power exchange with the ac network as a function of dc load current. Fig. 9 shows the active and reactive power operating range for a converter station with a voltage-sourced converter. Unlike conventional HVDC transmission, the converters themselves have no reactive power demand and can actually control their reactive power to regulate ac system voltage just like a generator.

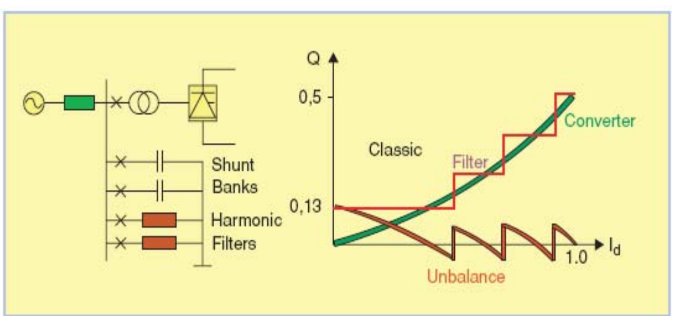

Fig. 8. Reactive power compensation for conventional HVDC

C. *Capacitor-Commutated Converter*

Converters with series capacitors connected between the valves and the transformers were introduced in the late 1990's for weak-system applications. These converters are referred to as capacitor-commutated converters (CCC). The series capacitor provides some of the converter reactive power compensation requirements automatically with load current and provides part of the commutation voltage, improving voltage stability. The overvoltage protection of the series capacitors is relatively simple since the capacitor is not exposed to line faults and the fault current for internal converter faults is limited by the impedance of the converter transformers. The CCC configuration allows higher power ratings in areas where the ac network is close to its voltage stability limit. CCC converters are used in the 4 x 550 MW asynchronous Garabi tie between Brazil and Argentina and the 2 x 100 MW Rapid City Tie between the eastern and western interconnected systems in the United States.

Fig. 9. Active - reactive power operating range for VSC based HVDC

V. HVDC CONTROL & OPERATING PRINCIPLES

A. *Conventional HVDC*

For conventional HVDC transmission one terminal sets the dc voltage level while the other terminal(s) regulates the (its) dc current by controlling its output voltage relative to that maintained by the voltage setting terminal. Since the dc line resistance is low, large changes in current and hence power can be made with relatively small changes in firing angle, alpha. Two independent methods exist for controlling the converter dc output voltage. These are 1) by changing the ratio between the direct voltage and the ac voltage by varying the delay angle or 2) by changing the converter ac voltage via load tap changers (LTC) on the converter transformer. Whereas the former method is rapid the latter method is slow due to the limited speed of response of the LTC. Use of high delay angles to achieve a larger dynamic range, however, increases the converter reactive power consumption. To minimize the reactive power demand while still providing adequate dynamic control range and commutation margin, the LTC is used at the rectifier terminal to keep the delay angle within its desired steady state range, e.g., 13-18 degrees, and at the inverter to keep the extinction angle within its desired range, e.g. 17-20 degrees, if the angle is used for dc voltage control or to maintain rated dc voltage if operating in minimum commutation margin control mode. Fig. 10 shows the characteristic transformer current and dc bridge voltage waveforms along with the controlled items Ud, Id and tap changer position, TCP.

B. *VSC-Based HVDC*

Power can be controlled by changing the phase angle of the converter ac voltage with respect to the filter bus voltage, whereas the reactive power can be controlled by changing the magnitude of the fundamental component of the converter ac voltage with respect to the filter bus voltage. By controlling these two aspects of the converter voltage, operation in all four quadrants is possible. This means that the converter can be operated in the middle of its reactive power range near unity power factor to maintain dynamic reactive power reserve for contingency voltage support similar to a static var compensator. It also means that the real power transfer can be changed rapidly without altering the reactive power exchange with the ac network or waiting for switching of shunt compensation. Fig. 11 shows the characteristic ac voltage waveforms before and after the ac filters along with the controlled items Ud, Id, Q and Uac.

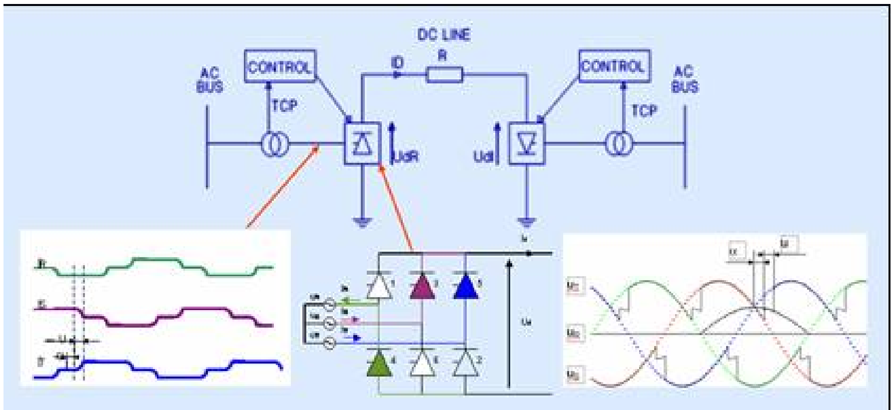

Fig. 10. Control of conventional HVDC transmission

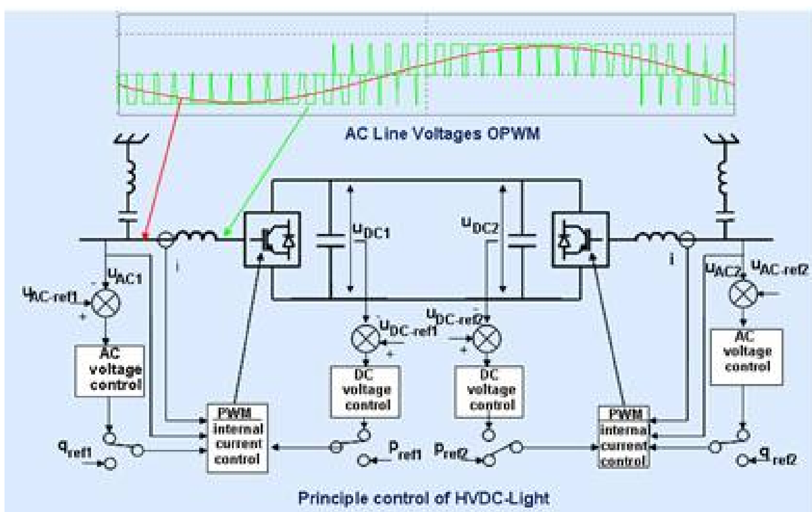

Fig. 11. Control of VSC-based HVDC transmission

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VII. Biography

Michael Bahrman received a BSEE degree from Michigan Technological University. He is currently US HVDC marketing manger for ABB Inc. He has 25 years of experience with ABB Power Systems including system analysis, system design, multiterminal HVDC control development and project management for various HVDC and FACTS projects in North America.

Prior to joining ABB, he was with Minnesota Power for ten years where he held positions as transmission planning engineer, HVDC control engineer and Manager of System Operations. He has been an active Member of IEEE serving on a number of subcommittees and working groups in the area of HVDC and FACTS.