Development in UHVDC Multi-Terminal and VSC DC Grid

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***Abstract*—This paper describes the development of LCC and VSC HVDC technology, focusing on LCC UHVDC multi-terminal application and VSC DC grid. An overview of operation aspects of the multi-terminal Northeast-Agra UHVDC project is introduced, and the challenges of quick and safe isolation of faulty equipment is addressed. Since more and more renewable energy is developed and needs to be integrated into the power grid, VSC HVDC technology has experienced great development in terms of high power and lower losses in the past 20 years. An expansion from point-to-point transmission to VSC DC grid is expected, therefore the challenges with VSC HVDC grid is discussed, such as operation flexibility, fast DC breaker, etc.**

***Index Terms*—DC Breaker, DC Grid, LCC HVDC, Multi-terminal, UHVDC, VSC HVDC.**

I. Introduction

HVDC can be divided into two subcategories: LCC HVDC and VSC HVDC. LCC HVDC is using thyristors as the main components for converting AC to DC and vice versa. LCC HVDC is mainly used in long distance bulk power transmission or BtB. In the past several decades, LCC HVDC has continuously been developed in the direction of higher voltage and higher capacity, for example, several 800kV/8GW UHVDC power projects are in operation and some projects of even higher ratings are under construction. VSC HVDC is based on power transistors, IGBTs (Insulated Gate Bipolar Transistors), as the converting components. IGBTs, being more controllable devices than thyristors, make VSC HVDC a more flexible technology than LCC HVDC, and easily adaptable for transmissions from renewable and variable power sources such as wind farms. In the past 20 years, much efforts has been put into development of control to lower the loss and also to increase the power capacity of IGBTs and cable technology. As more and more renewable energy has been developed, also due to the optimization use of DC transmission lines and operation flexibility, etc. point to point transmission has been extended into multi-terminal or DC grid application. Therefore the latest development of HVDC technologies is introduced, and the challenges for both multi-terminal UHVDC and VSC DC grid is addressed. Section II introduces the operation aspects, as well as the control strategy of multi-terminal LCC HVDC projects. Section III introduces the development of VSC technology and extruded cables. In section IV, the VSC DC grid application is introduced, key challenges, like control and protection strategy, DC breaker are discussed.

II. Development of MTDC

Multi-terminal UHVDC system refers to multi-converters or multi-stations in series or parallel connection. For parallel configuration, the converters can be either in the same station or separate locations. There are several aspects driving the application of multi-terminal UHVDC projects, i.e. amount of power to transmit is large enough, single phase two winding transformer may not be transportable; staging of construction; or flexibility in operation, etc. So far only the configuration of parallel converters has been used in practice, since it offers much more flexibility and lower overall transmission losses [1].

ABB has previously commissioned the Hydro Quebec - New England project, the first large scale multi-terminal HVDC transmission in the world. The latest project is the Northeast - Agra MTDC (NEA800) project, having a maximum converter rating of 8000 MW, supplying hydropower based electricity to 90 million people & is the first ±800kV UHVDC multi-terminal in the world.

1) *Introduction of the Hydro Quebec – New England project*

Figure 1, Quebec – New England MTDC

The project was originally a five terminal MTDC transmission. Since operation of the Des Cantons and Comerford converter stations were suspended, there are three remaining converter stations in parallel connection, i.e. Radisson, Nicolet, and Sandy Pond rated at 2250MW, 2138MW and 1800MW respectively. Radisson is operated as rectifier, Sandy Pond is operating as inverter, and Nicolet can be operated as either rectifier or inverter.

The advantage of the New England MTDC system is that it guarantees alternative sources of electricity to New England population centers like Boston. If Radisson goes off line due to maintenance or equipment failure, Boston could continue to receive power from Nicolet. Since thyristors are unidirectional, the converter in Nicolet station needs to change its polarity when changing operation mode.

2) Introduction of the Northeast-Agra Project

The North Eastern region of India has an abundance of hydro power resources scattered over a large area. A major load center in Agra, an industrial area, is located thousands of kilometers away. The power has to pass through the so called "chicken neck" area, a very narrow patch of land in the state of West Bengal having borders with Nepal on one side and Bangladesh on the other side.

The Northeast-Agra multi-terminal ±800kV/6000MW project, which planned to be in multi-terminal operation in 2016, will serve as highway of transmission hydropower in northeast to Agra. This is the first ±800kV UHVDC Multi Terminal system in world, and it has two rectifier stations; the first one is located in the North Eastern region in the state of Assam (Biswanath Chariali), and the second one is located 432 km away in the Eastern region in the state of West Bengal (Alipurduar). The inverter station with two terminals in parallel is located in the Agra region, located almost 1300 km from the nearest rectifier station. Each 800 kV converter is configured as single 12-pulse converter. Figure 2 illustrates the North East – Agra UHVDC project.

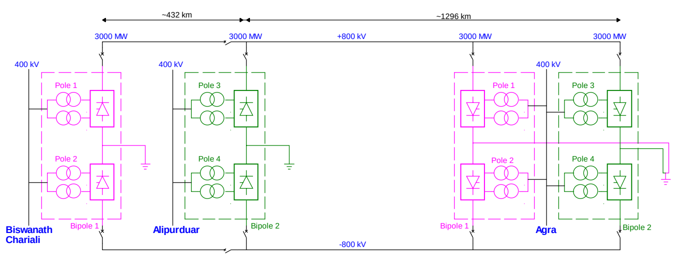


Figure 2, The North East – Agra UHVDC project

The Agra converter station will have two parallel converters in each pole, with a total bipolar power rating of 6000 MW and having a continuous overload rating at 33%. Thus even in the event of one converter outage, full rated power of 6000 MW can be transmitted to Agra.

3) Operation and control strategy - general

As each converter pole has a nominal rating of 1500 MW with an continuous overload rating of 2000 MW, it is possible to compensate for loss of any converter pole. If for instance Pole 1 in Agra is lost, Poles 2, 3 and 4 can supply the rated 6000 MW to the Agra region, see Figure 2. The consequential current loading of the Agra HVDC electrode will be 2500 A. In analogy with the above, also loss of one pole of the 432 km line between Biswanath Chariali and Alipurduar can be compensated by increasing the power flow on Poles 2, 3 and 4 to 2000 MW each. However, at loss of the 1296 km line between Alipurduar and Agra the power transmission capability is reduced to 4000 MW with an unbalanced neutral DC current of 5000 A. Thus, this line section is the most critical item regarding power transmission capability. However, even with significantly reduced voltage withstand capability, the faulty line will be suitable for metallic return thereby in most cases avoiding 5000 A earth return current.

The overall control and coordination of the converter poles in the multi-terminal HVDC link, including balancing of the power order to the converter poles are performed by the master control located in Agra.

4) Fault handling with and without telecommunication

An important design factor due to the high power rating is the capability of the control and protection system to handle all faults and disturbances with minimum impact on the healthy parts of the NEA800 HVDC link. The redundant telecommunication facilities and the master control is utilized for re-dispatching the load at outage of any converter or DC line for minimizing the disturbance of the power fed in to the Northern region/Agra system. However, the control and protective systems are designed for reliable operation and minimized disturbances even in the very unlikely event that both of the telecommunication systems are out of operation.

5) DC High Voltage High Speed Switches

Having more than two terminals in a transmission system opens the possibility to operate only parts of it. In the particular case of NEA800, the apparent parts that are attractive for disconnection for maintenance (planned or forced) are:

- A complete converter pole at either of the three stations
- A complete line pole between Biswanath Chariali and Alipurduar

Furthermore, it must be possible to perform the disconnection without having to make a complete pole stop. To achieve these objectives, the NEA800 transmission system is provided with high speed switches at selected locations, as shown in Figure 2. The devices are called high voltage high speed switches (HVSSS), since they are required to perform the disconnection and connection at high speed. Their physical construction will be very similar to that of AC breakers, but they will not be required to interrupt any current.

The advantages to use high speed switches are that the isolation can be performed with enough speed to meet the system requirement compared to using disconnectors, and it is very cost effective compared to using HVDC breakers.

III. Developments in VSC-HVDC

The technical development of VSC HVDC transmission technology as well as the extruded HVDC cable technology has been intense the last fifteen years.

Recent developments of HVDC Converters and extruded cables enable a set of different configurations with power ratings up to 1.8 GW at ± 500 kV voltage rating.

A number of projects show application examples and the maturity of the technology.

A. VSC HVDC schemes

1) Converter ratings

Since the introduction of HVDC Light in 1997 with rated 55 MW per block at a voltage level of ± 80 kV and an extruded

HVDC cable that enabled an underground system, ABB has constantly worked on increasing voltage and power ratings of the systems. The converter ratings and possible system configurations are presented in Figure 3. The DC-voltage rating has been chosen to correspond to the developed extruded cables, in order to provide an optimized design of the system. The current rating is determined by the size of the semiconductor that is used and the maximum current rating is 1740 A_{AC}, corresponding to 1800 A_{DC} The maximum converter rating is 1800 MVA for a single block.

	580 A_{AC}	1140 A_{AC}	1740 A_{AC}
+/- 80 kV_{DC}	100 MVA	200 MVA	300 MVA
+/- 150 kV_{DC}	190 MVA	370 MVA	540 MVA
+/- 320 kV_{DC}	400 MVA	790 MVA	1210 MVA
+/- 500 kV_{DC}	625 MVA	1220 MVA	1850 MVA

Figure 3, Converter rating as a function of rated DC-voltage and AC-current

To manage future requirements on for instance the Chinese market and make use of VSC-HVDC link versatile functionality in the grid, an increased current and voltage capacity is under development. With the use of state-of-the-art semiconductors, such as the BiGT, currents may be increased to 3 kA. With respect to voltage, VSC-HVDC could mimic designs and components used in LCC-HVDC, at least up to 800 kV in the medium term.

2) Project examples

The EWIC project [4] is an example of a HVDC VSC scheme that combines the novel features of a VSC converter with the basic features of all HVDC schemes. A large amount of renewables on Ireland can be supported with dynamic voltage support as well as a support with frequency control at varying renewable production.

Caprivi Link project is an asymmetric monopole and the first project with VSC and overhead lines, with the possibility to operate with and without metallic return. The VSC technology was selected since this project connects two weak grids and with additional requirements such as black start, voltage support and operation with very weak grids. The project is prepared to be extended to a bipolar scheme in a later stage, which shows how this technology can be an integrated part of a system planning with extension of power rating in stages [5].

(I) (II)

Figure 4, (I) Caprivi Link and (II) EWIC converter stations

The increase in voltage level to ± 500 kV in Skagerrak4 demonstrates the capability to deliver systems up to 1.8 GW, although this example is rated 2 x 700 Mw.

These examples prove that the technology has reached a maturity level both in rating and operating experience to support the transmission industry well in pursuing the optimal transmission grid solutions.

B. Extruded HVDC cables

Intensive research and development of extruded DC cables took place in the early 1990's. As a result, the first commercial project used 80 kV and a moderate power level. Innovation in DC insulation materials and manufacturing techniques led to the commercial deployment of extruded HVDC cable systems. After about 15 years of commercial experience, extruded HVDC cables have become a major player in the portfolio of HV cable products.

To date, 320 kV is the highest voltage for extruded DC cable systems in operation. Extruded HVDC cable systems enable, for example, solutions for the connection of remote energy resources to the loads, while circumventing public and land owner opposition to the construction of new overhead lines [6],[7].

1) Recent developments

To reach significantly higher voltage levels than 320 kV it was necessary to develop of a new insulation material. HVDC cable insulation material should have a low DC conductivity to avoid high thermal losses. Based on a lot of parameters for producing and qualifying full-scale cables the new compound is based on cross-linked polyethylene (XLPE) [8].

Figure 5, 525 kV cables with Aluminum or Copper conductor

Cable accessories (joints and terminations) are the other important parts of the development. Here, two types of joints are common: flexible factory joints (sea) and prefabricated joints (land). The pre-fabricated joint consists of a rubber body that is expanded onto the cable and placed over the conductor connector. Containers, specially built for the jointing on site, allows for maintaining a high level of cleanliness and control at site.

(I) (II)

Figure 6, (I) A 525 kV rubber body, (II) A specifically built container for underground cable jointing

The main development step of the 525 kV terminations was to go from oil-filled insulators to gas-filled. Here the development has benefitted from the 800 kV HVDC bushing development. The polymeric composite insulator offers maximum safety without the risk of shrapnel from explosions. Both the pre-fabricated joint and the termination use elastomer materials with non-linear field control properties in order to handle the DC electric field.

2) Qualification of HVDC cable systems

The 525 kV extruded HVDC cable system is in line with the qualification process according to international standards and recommendations.

Figure 7, Type testing of the 525 kV cable system

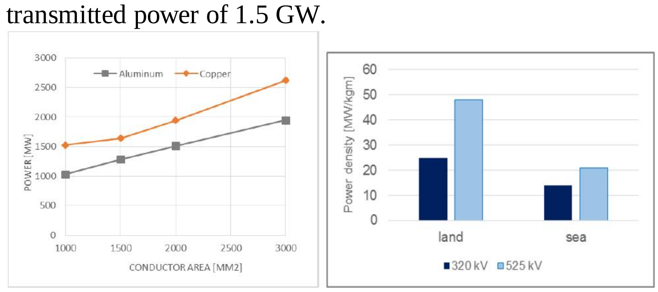
The latest document governing the qualification of extruded HVDC cables is the CIGRE Technical Brochure (TB) No. 496 which was issued in April 2012 [9]. A type test circuit is shown in Figure 5, test involves load cycling, including twelve 24h cycles at -972 kV (1.85 x U0), twelve 24h cycles at +972 kV and three 48h cycles at +972 kV. A cycle involves heating to the maximum conductor temperature 70ºC followed by cooling before next cycle starts.

Finally the load cycling impulse voltage testing follows, with a superimposed DC voltage at 525 kV. The impulse levels are here decided by the value the cable system can experience during service, times a factor of 1.15. The last step is a final DC voltage test at 972 kV before examination.

The prequalification test (also called long term test) involves a minimum of 360 days voltage test, according to a scheme in TB 496. Test set-up is basically the same as for the type test, with a cable length at least 100 m. The passed test was following TB 496. The final step in the test is a series of superimposed switching impulse tests with opposite polarity at a peak voltage level of 630 kV (1.2 x U0), in order to check the integrity of the cable after the long term testing.

3) Possibilities with a new more powerful cable system

The 525 kV extruded DC cable system can transmit at least 50% more power over extreme distances than previous solutions (i.e. the 320 kV extruded DC system). The technology offers the lowest cable weight per installed megawatt (MW) of transmission capacity, and the higher voltages provide reliable transmission and low energy losses. Figure 8(I) shows the transmitted power as a function of conductor area for both copper and aluminum as the conductor material. Compared with the 320 kV level the transferred power given as MW/kgm (power per kilogram of one meter cable) is about doubled for a land cable circuit and 1.5x for a submarine circuit for a transmitted power of 1.5 GW.



(I) (II)

Figure 8, (I) Transmitted power as a function of conductor area and metal for a cable pair, (II) Comparison of power density between a 320 kV extruded DC cable system and the 525 kV cable system (comparison for 1.5 GW or less, 525 kV Al, 320 kV Cu).

4) Next step

An increased use of undergrounding or submarine cables are foreseen, adhering to match converter ratings. Therefore consequently several manufacturers have indicated progress in voltages well above 525 kV. To fulfill visions such as the Global Energy Interconnection initiative, cables up to 800 kV would be desirable. This is also confirmed by work in for instance CIGRE on recommended voltages for HVDC, where levels of 500, 600 and 800 kV are described as suitable reference extra-high or ultra-high voltages.

IV. VSC HVDC GRIDS

In this section, the state of the art for existing VSC HVDC grids is firstly review. Then the DC grid control, protection and DC breaker technology is discussed.

A. State of the art for VSC HVDC grids

The first VSC HVDC grid was the ±160 kV Nan’Ao project, which was put into operation at the end of 2013 [10]. It is currently a 3 terminal system, with the stations rated 200MW, 100MW and 50MW. A future fourth 50MW terminal may be added at a later stage. Typical usage is to export excess wind power generation from the Nan’Ao island into mainland China.

Shortly after the Nan’Ao project, the five terminal ±200 kV Zhoushan project was put into operation in the middle of 2014 [11]. The five terminals are rated 400 MW, 300 MW and 3*100

MW respectively. Similar to Nan'Ao, the Zhoushan DC grid also helps to integrate distributed wind power generation, and can also provide emergency power assistance, in case the parallel AC network is disconnected, i.e. islanded operation.

B. DC grid control

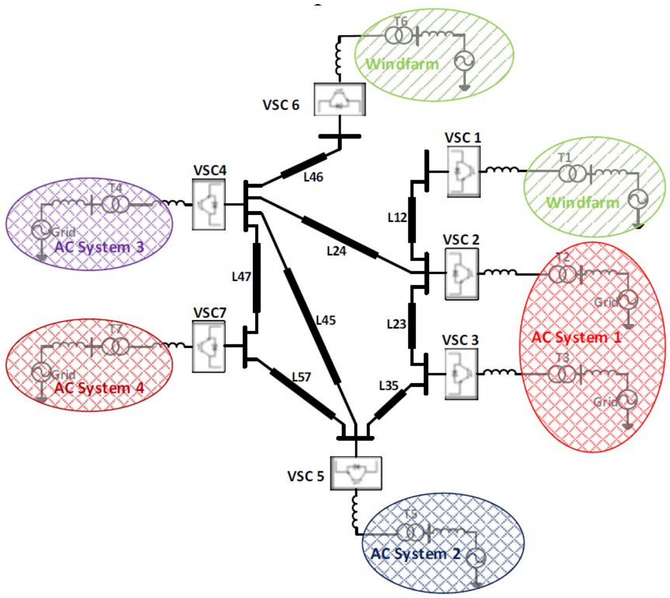


Figure 9, A 7-terminal DC grid using Optimal Power Flow

For a simple point-to-point VSC HVDC transmission, there is typically one DC voltage controlling converter, and one DC power controlling converter. Thus the DC power controlling converter will depending on the local AC network needs, either send or receive active power. The DC voltage controlling converter thus acts as a slack bus, adjusting its DC voltage in order to need of the other converter.

A simple DC grid control could be to expand the existing point-to-point concept, just by adding more DC power controlling terminals. Depending on circumstances, this may however put excessive strain on the DC voltage controlling terminal, and its related AC network. Therefore droop controls are used as a means to share the regulation burden of the whole DC grid, by all participating converters. This is indeed similar to how AC networks are operated. One common way to calculate what droop to use at each terminal, is by using local DC voltage measurements. This however has one major disadvantage, namely that due to the inevitable conductor resistance, the DC voltage varies across the DC grid. Therefore there will be an inevitable error in each locally calculated droop. This is different to AC transmission, for which any locally measured AC network frequency is common for the whole AC system. In order to have a similar shared reference level, the Pilot Voltage Droop concept was introduced [12]. The concept enables a very high accuracy control of each individual terminal when there is a sudden and large power mismatch, such as a converter trip in a terminal. If the overall power grid scheduling is available sufficiently in advance, the droops can be adjusted accordingly, thus giving maximum stability at large contingencies.

In order to lower the steady state losses in a DC grid, especially for a system with a high penetration of variable power sources, a proof of concept for a central optimal power flow calculation was made [13]. Arriving at optimal set points for all terminals in a 7-terminal system took 15ms, which indicates that this type of dispatching could be practically feasible.

C. Fast and reliable DC line protection

DC Grid protection is highly challenging due to two key reasons: The protection must be both extremely fast to detect (in the range of a few hundreds of microseconds), but still be 100% reliable and selective. In order for a protection to be that fast, it must rely only on local measurements. In [14], two novel protection algorithms were introduced in order to handle the challenging protection requirements, namely the TBFP (Transient Based Fault Protection) and the VDSCD (Voltage Derivative Supervised Current Derivative Protection).

TBFP is a form of travelling wave protection, which relies on each DC grid connection having a line inductance. Due to the inductance, there will be a small but measureable change in both DC current and DC voltage at fault inception. By using rapid sampling, the polarities of the current and voltage compared to pre-fault values can quickly be determined, thus providing a protection that is both fast and reliable.

The VDSCD protection extends the typically used DC voltage derivative protection by also including the DC current derivative. This adds the necessary selectiveness, since depending on the current derivative being positive or negative, a rapid determination of external or internal fault can be made, i.e. a fast and reliable DC protection.

D. DC breaker technology

As previously mentioned, rapid handling of DC faults is indeed a key challenge. For optimal operation of a DC grid, fast DC breakers are a practical requirement, since like an AC grid, a line with a permanent fault must be disconnected while the rest of the system continues operation. The Hybrid HVDC breaker concept [15] has received a lot of attention, since it shows promise to be a low loss solution while still having the necessary speed.

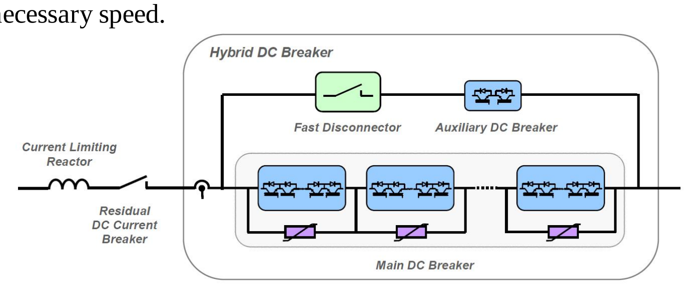


Figure 10, The Hybrid HVDC Breaker concept

In order to even further speed up the breaking process, the Commutation Booster was introduced [16]. By using the booster, the time taken to commutate the current from the mechanical branch to the semiconductor branch can be reduced significantly. As a matter of fact: The higher the fault current, the faster it can be commutated. Another big advantage with the booster is that it does not depend on any control or protection system action. Since an inductance always tries to keep the same magnetic flux, the current starts to commutate immediately to the semiconductor branch when there is an increase in DC current.

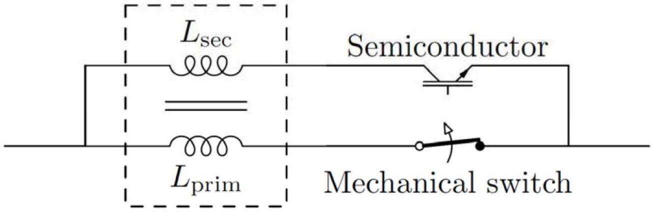


Figure 11, The Commutation Booster

Another possible design for low loss DC breakers suitable for DC Grid operation was introduced in [17]. The key merit of this concept is that it is fully mechanical, which could possibly make it both less costly, while at the same time more reliable. The main drawback with the mechanical circuit breaker compared to the Hybrid HVDC breaker is its slightly slower breaking time of ~5 ms compared to 2~3ms. Depending on specific application needs, ~5ms may be fast enough.

Figure 12, test setup for the mechanical HVDC breaker

V. CONCLUSIONS

The latest development of both LCC and VSC HVDC has been introduced, focus on the application of multi-terminal LCC UHVDC and challenges of DC grid.

The development of multi-terminal for LCC UHVDC has increased the operation flexibility significantly, which is very attractive solution in specific application, i.e. distributed generation to a major load.

The development of VSC HVDC Converters and extruded HVDC Cables has enabled new applications for transmissions system owners. Technology solutions for HVDC systems up to 1.8 GW that incorporate higher control and dynamic features enable high performance system as part of the planning toolbox for future transmission solutions.

For the future requirements on the Chinese customer and the visions of the Global Energy Interconnection, 800kV VSC converter and cables would be desirable, with the use of state-of-the-art semiconductors, such as BiGT, currents may be increased to 3kA.

Creating a DC Grid is challenging from many aspects, including control, protection and DC breakers.

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