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Recent advancements in HVDC VSC systems

HVDC and Power Electronics technology and development

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SUMMARY

The technical development of voltage source converter (VSC) high voltage direct current (HVDC) transmission technology as well as the extruded HVDC cable technology has been intense the last fifteen years. The increase in power and voltage capability has enabled new applications for VSC based HVDC.

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.

KEYWORDS

VSC HVDC Converters, extruded cables,

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Introduction

The technical development of voltage source converter (VSC) high voltage direct current (HVDC) transmission technology as well as the extruded HVDC cable technology has been intense the last fifteen years. The power electronic and material sciences are key in enabling the industry to propose transmission solutions that have not been available before. The increase in power and voltage capability has enabled new applications for VSC based HVDC, giving a new set of tools for transmission system owners to solve the challenges in building a flexible and agile system that can handle the challenges today and in the future.

VSC HVDC schemes

The choice of the most suitable VSC HVDC transmission scheme differs, depending on the application. Traditionally subsea or overhead line HVDC transmission systems have connected two asynchronous ac-grids, enabling energy trading between these systems. In recent years applications such as interconnection of renewable generation offshore, embedded HVDC and VSC BtB have enabled much more flexible transmission systems. This development has transformed HVDC from a niche solution to one of the key building blocks in grid planning.

Ratings and system features

Since the introduction of HVDC Light in 1997, ABB has constantly worked on increasing voltage and power ratings of the systems. The first commercial system was rated 55 MW per block at a voltage level of +/- 80 kV, with an extruded HVDC cable that enabled an underground system that was state of the art. The development has focused on enabling new applications for the customer and a number of configurations has been developed to facilitate this. The converter ratings and possible system configurations are presented in figure 1. 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 voltage of the converter is chosen to enable a base design of the converters that would provide better interoperability and modularity of the systems. 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, 1800 MVA for a single block, is large enough to extend beyond the allowed size of a single power block in many transmission grids, due to the impact of a loss of system.

	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 1. Converter rating as a function of rated DC-voltage and AC-current.

The HVDC system configuration of a project depend on the application and system features. The transmission medium between the converter stations can be subsea or underground cables, overhead lines and even a mixture of both. All of these solutions as well as the selection of symmetrical or unsymmetrical monopole or bipolar configuration have been demonstrated in delivered projects or projects under construction [1]. A schematic view of the possible configurations are displayed in figure 2 below. The symmetrical monopole has been the most common solution for projects so far, both for subsea and underground transmission scheme. This solution offers the highest power density of the converter, due to lowest number of main circuit apparatus in the system. In case of a single

failure is not allowed to result in total loss of power, a bipolar scheme should be selected. This would enable that only 50 % of the power is affected by a trip of one converter.
The bipolar converter scheme demands four converter blocks per system and a number of additional main circuit apparatus on the dc-side to enable bipolar operation during normal operation and monopole operation during an (n-1)-event.
Another major difference is that the transformer will not be subject to any DC-stress in symmetrical monopole while this is the case for asymmetrical monopole and bipole.

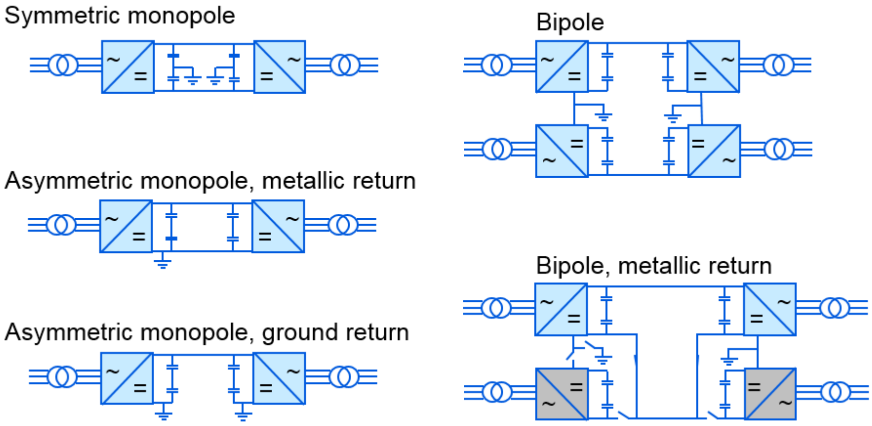

Figure 2. System layout of the VSC converter system

Project examples

The EWIC[2] project 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.
An example of a staged approach is the Caprivi Link project that was built for security of supply reasons in Namibia by securing direct access to power from Zambia. It was built as an asymmetric monopole, as per above, with the possibility to operate with and without metallic return. The VSC technology was selected since this project connects two weak grids, which makes VSC based HVDC the only solution that could fulfil requirements such as black start, voltage support and operation with very weak grids. It is also the first project with VSC and overhead lines. 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.[3]

(I) (II)

Figure 3. VSC Converter Stations, (I) Caprivi Link and (II) EWIC

In the Mackinac Back-to-Back(BtB)[4] an additional system feature has been included. The HVDC system can operate in an emulation mode, mimicking an AC-line during grid transients so that the operator can retain stable control without thinking of the HVDC as a special device. This exemplifies the great freedom in planning and system operation that an introduction of HVDC permits.

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. Such a power rating fits well with many transmission system's stability requirement restrictions of largest allowed power unit in case of tripping..

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.

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 high voltage direct current (HVDC) cable systems in different parts of the world. After about 15 years of commercial experience, extruded HVDC cables have become a major player in the portfolio of HV cable products.
Over time the number of applications for HVDC cable systems have increased. To date, 320 kV is the highest voltage for extruded DC cable systems introduced for service. 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 [5][6].

Recent developments

In order to reach significantly higher voltage levels than 320 kV it was necessary to start development of a new insulation material. A good HVDC cable insulation material, beside all the normal requirements for HVAC cables, such as good mechanical, chemical and electrical properties, (e.g. high breakdown strength), should meet additional requirements due to the DC voltage. The insulation should have a low DC conductivity to avoid high thermal losses. (The conductivity of insulation materials increases with the electric field and temperature, therefore higher conductivity increases the risk of thermal runaway and electrical failure).
Several material compositions were evaluated during the initial stages of the development. Based on a lot of parameters for producing and qualifying full-scale cables the new compound is based on cross-linked polyethylene (XLPE) [7]. The development of optimal process parameters and quality control techniques has enabled the capability of producing and delivering extruded HVDC cables for land and sea applications at higher voltage levels.

Figure 4: 525 kV cables with Aluminium or Copper conductor.

Cable accessories (joints and terminations) are the other important parts of the development. Joints are used for connecting two cable ends in an extruded cable system. Here, two types of joints are common: flexible factory joints and prefabricated joints. Often they may also be referred to as sea (factory) and land (prefabricated) joints. This relates to the transport situation on land, where short cable sections are transported to the laying site on drums, and many joints need to be installed on site. In contrast, the boats transporting sea cables to the site may load hundred kilometres and more, and required jointing can be done prior to loading and transport under factory conditions.

The new 525 kV factory joint resembles the actual cable as, in principle. It uses the same materials, e.g. semiconducting and insulating XLPE. This is similar to factory joints for lower voltages. The cable conductors are welded and the semiconducting and insulating layers are restored, utilizing moulding or extrusion. Generally this process is a challenge as it is time consuming and requires a high degree of cleanliness in the different production steps. This is further pronounced for the 525 kV factory joint, which has additional cleanliness requirements and quality control measures. The factory joints are produced with the same insulation thickness as the cable, leading to similar flexibility and mechanical properties.

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 (Figure 5).

Figure 5. (a) A 525 kV rubber body, (b) A specifically built container for underground cable jointing.

The development of the terminations also needed a new technology when going from 320 kV to 525 kV. The main step 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.

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. The latest document governing the qualification of extruded HVDC cables is the CIGRE Technical Brochure (TB) No. 496 which was issued in April 2012 [8].The electrical testing scheme for cable systems with VSC (Voltage Source Converter) followed the TB 496. The type test involves load cycling, including twelve 24h cycles at -972 kV (1.85 x U_0), 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. A type test circuit is shown in Figure 6.

Figure 6: Type testing of the 525 kV extruded HVDC cable system.

The prequalification test (also called long term test) involves a minimum of 360 days voltage test, including periods of load cycling, full load and zero load, according to a scheme in TB 496. The overall cable system set-up is basically the same as for the type test, except that there is a requirement that the cable length is at least 100 m. The passed test was following the VSC scheme in 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 U_0), in order to check the integrity of the cable after the long term testing.

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 G shows the transmitted power as a function of conductor area for both copper and aluminium 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 (Figure 7).

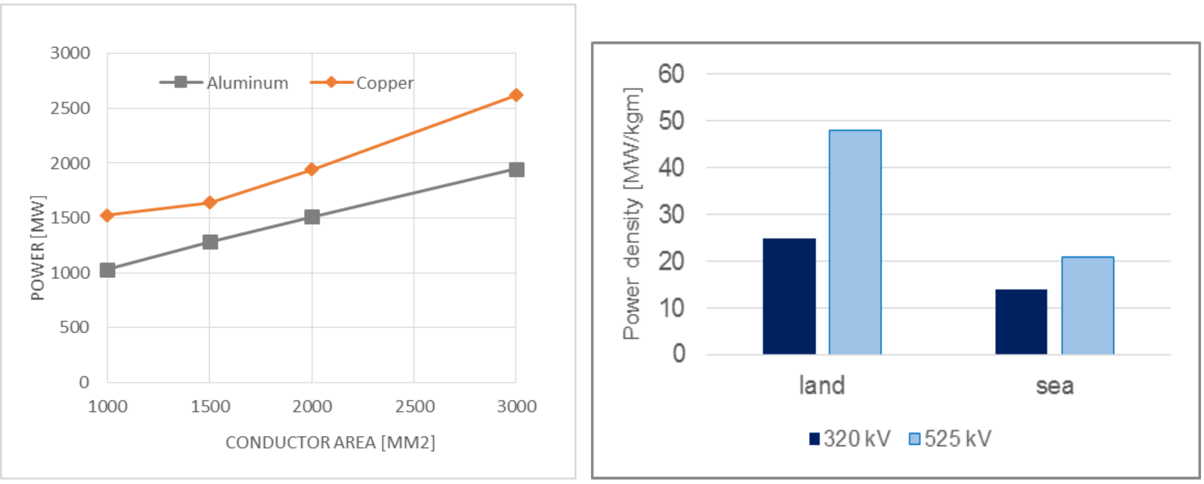

Figure 7: (a) Transmitted power as a function of conductor area and metal for a cable pair, (b) Comparison of power density between a 320 kV extruded DC cable system and the 525 kV cable system (comparison for 1.5 GW or less, 525 kV Al, 320 kV Cu)

Conclusions

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.

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