HVDC Solutions for Integration of the Renewable Energy Resources

Comparison of Technical Alternatives and System Configurations

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Abstract—**Today HVDC transmission plays an important role for smooth integration of renewable energy into power grids. This paper presents an overview on different technological solutions for connection and transmission of large amounts of power up to the gigawatts-range. Pros and Cons of different system configurations are discussed. Examples of projects including latest converter technologies are given.**

Keywords-High-Voltage Direct Current (HVDC); Voltage-source Converter (VSC); Line-commutated Converter(LCC)

I. Introduction

Increasing use of renewable energy is a global trend worldwide. Integration of such large amount of new power supplies into existing power infrastructures is a major challenge. Most of the valuable renewable resources are located in remote areas far away from the load centers. Thus, one of the major challenges lies in transporting the energy generated from these resources efficiently to communities who consume the power. Furthermore, grids need to be kept stable during all operation conditions. With decreasing amount of rotating masses of conventional power plants the system strength is reduced more and more. Hence, reliable operation even under low short circuit power as well as under changing system conditions characterized by large-scale fluctuating regenerative energy sources, such as wind and solar power, is required.

High-Voltage Direct Current (HVDC) transmission plays an increasingly important role to manage power system operation under the above mentioned conditions which is described in the following sections

II. HVDC Technologies

Since many decades HVDC transmission has been successfully used for three main categories of applications:

- efficient long-distance transmissions where ac solutions are not competitive regarding costs and losses
- (submarine) cable transmission
- back-to-back links allowing dedicated power exchange between asynchronous power systems.

For integration of renewables, especially the first category, HVDC long-distance transmission, has been widely used. Examples are bulk-power transmission of energy generated from hydro in countries like China and Brasil. Typically, the economic break-even for HVDC transmission compared to ac transmission is at a distance of more than 600 to 800 kilometers.

The HVDC technology widely used for such applications has been Line-commutated converters (LCC). Proper operation such converters requires a minimum ac system strength. A stable ac system voltage (“line voltage”) is needed to force commutation from one valve to the next within a converter bridge. LCC technology development started in the 1940s using mercury arc valves. In the 1970s availability semi-conductors allowed to apply thyristor valves instead which was a milestone in the HVDC history. In the following decades an impressive development of the thyristor technology in terms of blocking voltage, silicon diameter and reliability increased the power capability of HVDC transmission considerably and thus led to a significantly increased number of applications worldwide.

Today, LCC solutions are complemented by voltage-sourced converter (VSC) systems, a relatively young application in the field of power transmission. Based on availability of improved semi-conductors like high-power IGBTs, it was possible to apply self-commutated converters in HVDC solutions. The additional turn-off capability of such devices compared to thyristors allows operation of the converter independent of the ac system voltage and hence enables application in very weak or even islanded AC networks. Furthermore, black-start capability as well as fast and flexible reactive power control independent of the transmitted active power is possible.

A major boost for this technology was the transition from two- and three-level topologies to Modular Multilevel Converter (MMC). A large number of modules acting as voltage sources allow adjusting to sinusoidal system voltage wave shapes in a very accurate way so that harmonics are practically not generated. Hence, typically no harmonic filtering is required anymore. Furthermore, compared to pulse-width modulation a significantly lower switching frequency can be applied reducing power semi-conductor switching losses dramatically. The world's first VSC HVDC project using MMC topology is the 400 MW Trans Bay Cable Project in San Francisco which started commercial operation in 2010.

Another important aspect is the dc cable technology. As restricted right-of-ways for new transmission corridors are a common topic of discussion in many countries the increasing use of underground transmission is expected. In the past, nearly all HVDC cable projects with LCC technology were built using either oil-filled or mass-impregnated dc cables. XLPE cables - as broadly used for ac applications - were not possible to be applied due to the fact that they are sensitive to dc voltage polarity reversals. While dc voltage polarity reversal is required for LCC schemes to enable reversal of power direction, VSC technology allows to reverse the dc current and hence can operate continuously in the same voltage polarity. As consequence, with VSC HVDC the number of projects using XLPE dc cables has increased significantly. In parallel, dc voltage ratings of XLPE cables have increased stepwise, reaching currently up to 525 kV. It should be noted that XLPE cable technology also simplifies installation of longer land cable sections.

For new transmission projects a careful evaluation should be done to determine which of both HVDC technologies, LCC or VSC, provides the optimal solution. Both have their individual pros and cons. System aspects may lead to exclusion of one technology while other aspects including losses or economic aspects may lead to preference of the other one. However, not only the converter technology but also the selection of the most adequate dc circuit configuration is important for finding the best technical and economical solution for the specific project. The following sections describe possible configurations of the converters and arrangement of the dc circuits and may be used as first guidance for determination of the preferred solution.

III. LCC Solutions

A. Ratings and Applications

Due to the high current capability of thyristors LCC technology is typically the preferred solution for low loss high power ratings. Nowadays, several thyristor types and sizes are available enabling a wide range of applications. The upper edge of power capability is formed by thyristors with 6-inch diameter and a blocking voltage of 8,500 volts allowing DC currents of more than 6,250 amperes. Series connection of large numbers of thyristor levels and modular converter valves enable solutions for dc voltages up to the Ultra High Voltage (UHV) range. Several HVDC projects with ±800 kV dc voltage level are meanwhile in operation in India and China. In Brasil an 800kV HVDC project is currently under construction. Another milestone will be the application of a voltage level of 1100 kV, the first project of this kind is currently under construction in China. In bipolar configuration this solution allows to design transmission systems for more than 10 GW. In China several of such links have been constructed to transmit hydro generated power from the mountain areas in Central China to the load centers in the East. With UHVDC economic power transmission bridging distances of several thousand kilometers is possible.

B. DC Circuit Configurations

Typical configuration for bulk power transmission is to arrange the converter system as a bipolar link (see Figure 1). In such a configuration two converters are connected in series with the common connection grounded or floating close to ground potential. Two pole conductors are operated on high-voltage potential with opposite polarities. A return path between both terminals could be realized either by an additional conductor (typically medium voltage) or by sea or ground electrodes. Ideally, during normal operation the converters of each pole are operated at the same power level which avoids an unbalance current through the return path. Hence, transmission losses can be minimized.

Advantages of a bipolar configuration are that the link includes redundancy – at least for 50% power rating. An outage of any converter or transmission line still allows operation with the remaining converter or dc line.

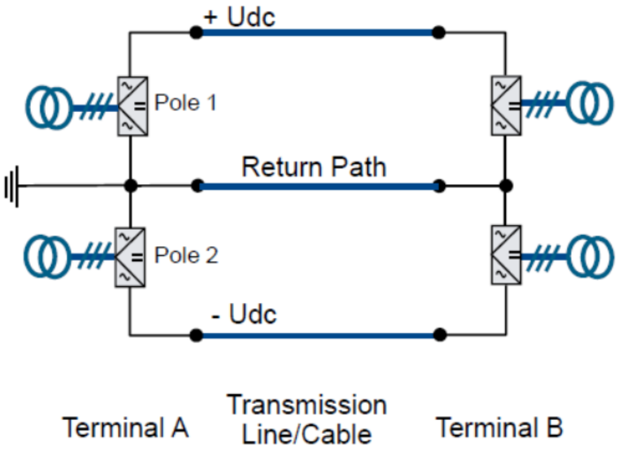

Figure 1. Bipole, Single converter per pole

For very high power ratings and dc voltage levels further modifications in the configuration of a bipolar link may be reasonable: The converter system of one pole can be itself arranged as a series connection of two converters (see Figure 2).

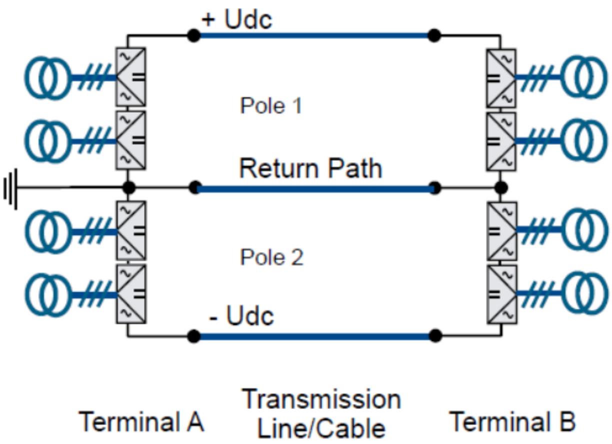

Figure 2. Bipole, Two series-connected converters per pole

It is obvious that such a configuration is more expensive compared to a single converter per pole solution. However, it provides a higher power availability as the maximum power lost in case of a single converter outage is only 25%. By including some overload capability in the converter ratings the amount of power lost during such contingency can even be further reduced.

Often another reason may also require splitting up the pole power in two converters: large and heavy equipment - as the converter transformers - may otherwise not be possible to be transported especially if the converter station is located in mountain areas.

An alternative way to split up the power ratings of one pole is the parallel connection of two converters. The current rating of each converter is reduced to 50%, however, in this case full voltage rating is still required for each converter increasing the costs of the converter station compared to the series converter solution. Advantage is that in case of a converter outage, the whole link can continue operation at full dc voltage which reduces transmission line losses.

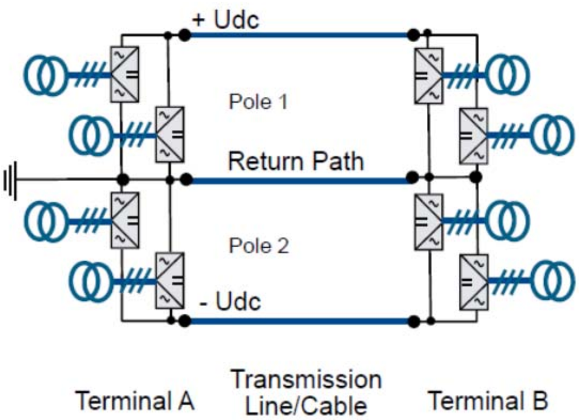

Figure 3. Bipole, Two parallel-connected converters per pole

In principle, the parallel connected converters could also be geographically separated. In such case, a multi-terminal configuration is formed. Application of LCC technology for multi-terminal links is feasible but typically limited to 3 or 4 terminals maximum. Some restrictions apply if such a link should be operated with full flexibility. As mentioned before a reversal of the power direction is only possible by reversal of the dc voltage polarity. Hence, - if only one terminal of a multi-terminal link should be required to reverse power direction – additional equipment like voltage reversal switches are required and converter equipment needs to be insulated for full voltage on both terminals.

Bipolar arrangements are also very well suitable for a staged development of a project. While typically the complete dc lines are installed from the beginning, the converters could be installed in one pole only in the first stage. In a later stage, the system could be expanded with another pole and hence adapt the required investment to the specific business case.

For completeness another configuration is shown, even though it is mainly focusing on long dc cable connection: the rigid bipole. The dc circuit consists of two high voltage conductors only (see Figure 4). As a return path does not exist this further reduces the costs of the project. However, disadvantage is that in case of a fault in one converter, the complete link has to interrupt complete power transfer for a few seconds. After fault clearing and re-configuration of the dc cables the link could resume power transmission at remaining 50% rating. In case of a permanent cable fault in one system, the complete link has to be shut down permanently.

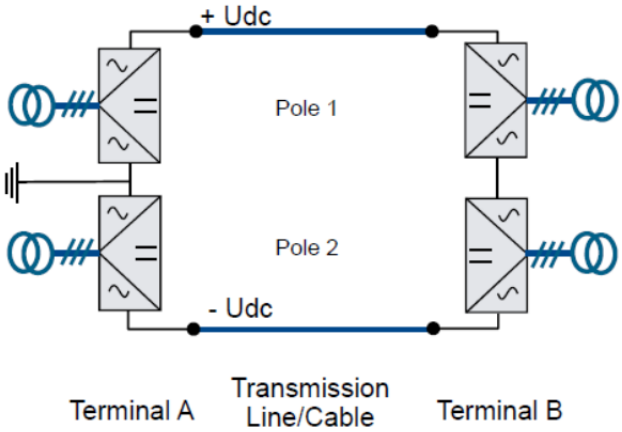

Figure 4. Rigid Bipole

C. Space requirements

Converter operation of LCC solutions consumes reactive power which typically needs to be compensated at the point of common coupling (PCC) at the ac system. Furthermore, the converters act as source for harmonic currents which requires filtering in order not to disturb the ac system voltage. Both requirements typically lead to a relatively large space demand for the ac switchyards allowing allocation of ac filter and shunt capacitor banks.

IV. VSC SOLUTIONS

A. Ratings and Applications

Even though, power semi-conductor technology as applied in VSC solutions is developing rapidly, IGBTs still have a significantly lower current rating compared to thyristors. Projects in operation have dc current ratings of up to 1.6 kAmps. Next generation of power modules are available increasing the current ratings to more than 2 kAmps. Overload capabilities are typically not inherently available.

Since most of the VSC HVDC projects in the recent years included cables in the dc circuit, selection of the rated voltages was mainly driven by the available cable technology. As described above, XLPE cables play an important role for VSC solutions, even though also mass-impregnated cables can also be applied. Similar to LCC technology the converters are arranged by series connection of converter submodules. Practically, there is no specific voltage limit for rating of a single converter. Maximum rating of a single converter in operation is currently 640kV (for a ±320kV system). However, converters with voltages of 800 kV (for a ±400 kV system) are under construction. Solutions for operating voltages to ground of up to 525 kV are available. Currently single converter systems up to 1000 MW are in operation. For bipolar links 2000MW at ±500 kV are possible. It is expected that the power ratings, voltages and currents, will further increase continuously in the next years.

Major difference compared to LCC applications is the self-commutation capability of VSC converters, i.e. the ac output voltage phase and amplitude can be controlled independently of the connected ac systems. That means that flexible reactive power control is possible independent of the transmitted active power. This allows fast and flexible control of the ac voltage which is important especially for weak ac systems. Hence, the VSC HVDC includes also the functionality of a FACTS device. Operation even with islanded systems is possible. Examples are connections to large offshore windfarms as introduced in the following chapter. If required, the VSC HVDC could even take over the role to control voltage and frequency of the ac system. Such a feature can also be applied in case of a large ac system collapse ("blackout"). The VSC HVDC can support fast recovery the ac system using its system recovery ancillary services (SRAS), i.e. it provides "blackstart" capability.

Most of the VSC schemes currently in operation are using so-called half-bridge converters. Such converter configuration allows operating the dc system with constant dc voltage. Reducing or reversing the dc voltage is not possible. Hence, in case of disturbances, e.g. due to a dc side fault, the complete system must be tripped by opening the ac side circuit breakers. For pure cable systems on the dc side such solution is commonly accepted since faults on the dc side are rare and recovery is not required since the faults are permanent. However, for overhead line applications where frequent lightning strikes could lead to ground faults, a recovery is typically desired. If the ac system can tolerate the duration of power interruption caused by switching of ac circuit breakers half-bridge converters are still the preferred solution. However, meanwhile new solutions are available allowing to clear dc side faults in a fast and effective way. One solution is to use full-bridge converters which enable controlling the dc voltage. In the event of a dc side fault, the dc voltage can be reduced to zero or even slightly reversed to quickly extinguish the fault. After de-ionization time has passed the system can be ramped up again and power transfer can continue. Such a feature reduces the power interruption time to a few hundred milliseconds. The first application of a VSC HVDC with full-bridge converters is currently under construction in Germany. The Ultranet Project is the first of several planned Corridor projects as part of the "German Energiewende" initiative which shall transmit renewable energy generated from wind power in the North of the country to the load centers in the South. By this, nuclear power plants in the South can be replaced step-by-step.

B. *DC Circuit Configurations*

The simplest configuration for a VSC HVDC is the so called "symmetrical monopole" (SMP). The term "monopole" stands for a single converter as operating unit. The DC circuit is not solidly grounded and operated with both pole conductors in a balanced mode with symmetrical DC voltages of both polarities. Balancing of the voltages can be achieved via different concepts, e.g. by installing star-point reactors. (see Figure 5).

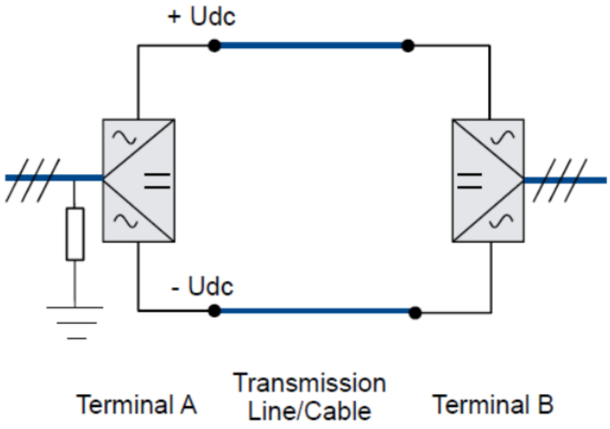

Figure 5. VSC in Symmetrical Monopole (SMP) configuration

The symmetrical monopole is most suitable for cable connections as then the dc circuit is not exposed to high unbalance effects, e.g. due to pollution. In case of applications with overhead lines special consideration must be paid to avoid adverse effects.

The maximum rating of a SMP is typically defined by the maximum voltage and current level of a single converter. An economical design is typically limited at ±400 kV for a SMP. Assuming a dc current rating of 2 kAmps, a maximum rating of approx. 1400 to 1600 MW is possible.

For larger power ratings and/or in order to provide some redundancy an arrangement with two (or more) SMPs connected in parallel on the ac side are possible. Such a configuration has been chosen for the most powerful VSC link currently in operation, the Inelfe Project connecting France and Spain, 2 x1000 MW (see Figure 6).

Figure 6. Inelfe Project, France-Spain, 2 x 1000 MW

Currently under construction is the first Indian VSC HVDC project with the same configuration and rating, connecting Pugalur to North-Trichur (Kerala).

SMP configurations are also used to provide grid access for offshore wind farms in the European North Sea. In the German North Sea several HVDC VSC links have recently been built and put into operation. The converters are installed onto large offshore platforms as shown in Figure 7.

Figure 7. Offshore Platform Sylwin 1, 864 MW (Copyright: TenneT)

An alternative arrangement to two SMPs is the bipolar or rigid bipolar configuration as discussed in the LCC section above (see Figures 1 and 4). This allows to further increase the voltage rating for the transmission circuit and includes two converters per station in each system. In this case - compared to two separate SMPs - not four but only two high voltage conductors are required plus possibly an additional medium voltage conductor - if a metallic return path is desired. Especially for long-distance transmission schemes this could be the most economical as well as the most loss optimized alternative.

C. Space Requirements

In contrary to LCC solutions, VSC HVDC does not require additional reactive power compensation and also typically no harmonic filters for most of the converter designs. Hence, the ac switchyard layout is typically rather simple. However, converters and consequently also converter halls are somewhat larger comparted to LCC solutions as they need to include also significant amount of dc storage capacitors.

In general, VSC solutions can be designed compacter compared to LCC solutions and are therefore more suitable for solutions where space restrictions exist.

If required, additional measures are available to further optimize space demand. On the ac side a connection to the power system via ac gas-insulated switchyard (GIS) is possible. Furthermore, as new technology meanwhile also on the dc side a dc compact switchgear (DC CS) is available. A first application is currently under implementation for a 320 kV project. (see Figure 8).

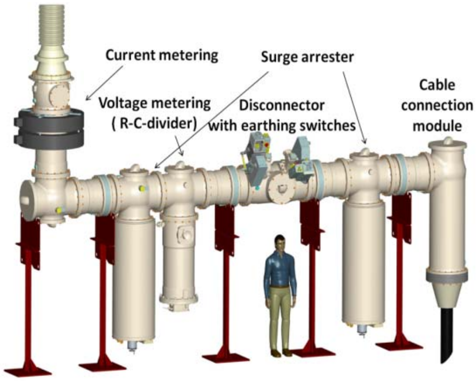

Figure 8. DC Compact Switchgear (DC CS), 320 kV

V. CONCLUSION

In conclusion, a broad portfolio of HVDC solutions exists enabling smooth integration of renewal energy in the Transmission Grid. The HVDC Back-to-back and long distance transmission systems using LCC & VSC technology secure sustainable access to huge renewal energy resources like wind, solar, and hydro. DC highways enhance existing ac power infrastructures. As the HVDC technology is a proven solution worldwide, it enables an important step in the direction of environmental sustainability of power supply.

BIOGRAPHICAL INFORMATION

Marcus Haeusler received the Dipl.-Ing. degree in electrical engineering from the University of Karlsruhe (KIT), Karlsruhe, Germany, in 1992. Since he joined Siemens AG in 1992, he has been working on HVDC system engineering for many HVDC projects worldwide. He has been responsible for coordination of R&D activities for UHVDC technology within Siemens. In 2007, he and his team received the Siemens TOP Plus Award for outstanding developments in the area of UHV DC. He is principle expert and lead engineer for VSC HVDC systems at Siemens Energy Management, Large Transmission Solutions, Erlangen, Germany.

Mr. Haeusler is active in several technical committees of the International Electrotechnical Commission (IEC) and chairman of TC 115, HVDC systems.

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