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ABSTRACT

Power transformers are integral in the HVDC transmission systems and provide multiple functions. Correctly optimised transformers lower the cost for other equipment in HVDC schemes. This article describes the basics of HVDC and gives a view of where the HVDC development stands today. Both the LCC and VSC technologies are described, as well as newer converter concepts that lower losses and harmonic stresses. Finally the authors call for innovative solutions in order to boost the power density of transformers.

Keywords

HVDC, LCC, VSC, switching methods, offshore transformers

Transformers in HVDC transmission

The social wind is favouring DC transmissions

1. Why do we need power transmission by direct current?

The transmission of bulk electricity in the last 120 years has revolutionised the way we live and work by bringing the needed energy to move the industrial production machine wherever it was located.

From the early days of the "battle of the currents" between direct current (DC) and alternating current (AC), our industry has been fuelled by continuous innovation and challenged by ever increasing demands to reduce costs, be more efficient, reduce environmental impacts, promote social inclusion, and reduce emissions of pollutants that might cause climate change.

Despite the dominance of AC transmission throughout the 20th century, since the 1950s, high voltage direct current (HVDC), using line-commutated converters (LCC), has gradually re-established itself as a niche application. Initially there were no controlled high-voltage switches, which were capable of carrying out the task of converting AC into DC and back again. Hence early systems relied on cascading motor-generator schemes. In the middle of the 1950s, however, mercury-arc valves were developed which enabled the early "modern HVDC" schemes to be built without moving parts.

With the discovery and usage of semiconductor switching devices such as transistors, and particularly the thyristors in the 1960s, solid-state technology began to replace the older mercury-arc technology, bringing improved reliability and higher power ratings to HVDC.

HVDC interconnectors allowed the delivery of bulk power in ever-increasing voltage ratings with much reduced losses compared to AC systems. This made it possible to bring vast hydropower resources from far away dams to load centres, or interconnect regions for mutually beneficial energy exchange with further power systems stability improvements. Ultra-high-voltage DC transmission (UHVDC) nowadays is rated at 800 kV DC and rated currents in the range of 5.0 – 6.0 kA, thus achieving the transmission capacity of 8 GW with one single bipole (two conductors). R&D activity is already in course to extend the voltage further to 1,000 kV. There are several schemes in operation, under construction or being planned with basis on 800 kV UHVDC technology. It enables regional bulk-energy exchange and use of remote hydroelectricity.

In the first decades of the 21st century, the power industry challenges have again dramatically changed. Environmental concerns, the skyrocketing cost of land for new transmission lines and substations with severe restrictions for planning permits, as well as the price of energy itself are making energy managers and engineers look into HVDC transmission systems, and into how both AC and DC technologies may complement each other to result in higher system efficiency.

Traditionally HVDC would be used for a few typical cases: 1. for long distances, 2. when long sub-sea or underground cables are needed, or 3.when frequency conversion or asynchronous connection was necessary.

The first case is when the transmission distance is such that bulk power transmission becomes cheaper to be transferred with HVDC than using HVAC. The breakeven distance, depending on specific cases could be between 450 – 600 km. This happens because HVAC lines are more expensive than HVDC lines. One bipolar HVDC transmission system with two conductors, a positive and a negative one is equivalent to a double circuit AC transmission line for the same transmitted power. Hence six vs. two conductors for the length of the transmission motivate the adoption of DC. Furthermore, for the same transmission voltage level, the DC transmission losses are only a fraction of those in AC. On the other hand, the terminals, including converter equipment are more expensive with the HVDC compared with conventional substations. Thus, it pays off using DC for a certain minimum distance or longer.

UHVDC transmission lines rated at 800 kV DC and 5.0 – 6.0 kA, transmit up to 8 GW of power

When using AC cables, the reactive power generated by the cable capacitance becomes an issue because the longer the cable, the higher its charging current. There is a distance for which all the cable thermal capacity is consumed by reactive power without any active power being transferred between cable terminals. Therefore, at industrial frequencies (50 or 60Hz), it is practically difficult to transmit large amounts of electric power through long cables. The practical distances vary with the different degrees of compensation and if intermediate compensation stations are utilised. Nonetheless, it would be impractical to attempt and more costly to employ HVAC cables for distances above circa 50 km.

Currently HVDC systems with LCC technology, which is the traditional or classic HVDC solution, has through continuous R&D and improvements in material and computing process in design been able to reach high power transmission capabilities which will further increase to reach 10 GW per bipole, which is an enabler for regional interconnectors. However, HVDC is also becoming popular with much lower power ratings, around 1 GW due to the integration of variable power generating assets, such as wind farms.

In the past decade, the environmental requirements pushed by the society to reduce emissions of greenhouse gasses (GHG), implied in a massive investment of power generation assets based on renewable energy sources. This shift in power generating sources brings the operational need to more usage or power transmission. The transmission is now not only needed to bring the power from its generating point

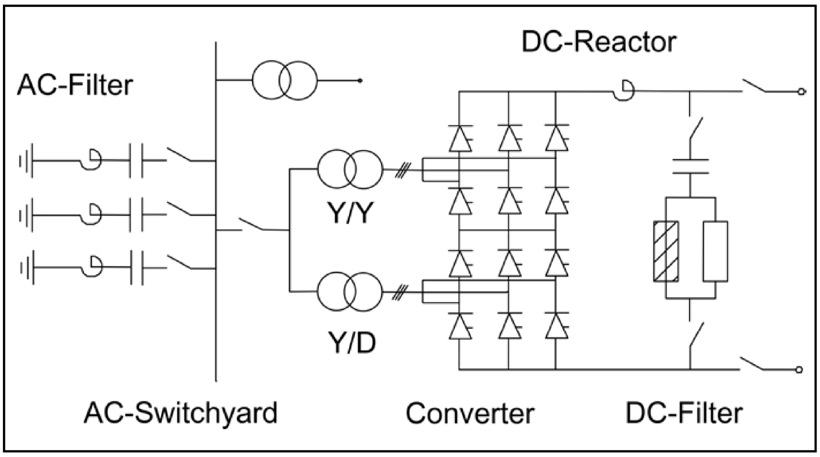

Figure 1: A basic overview of a classic HVDC power transmission station based on LCC technology [1]

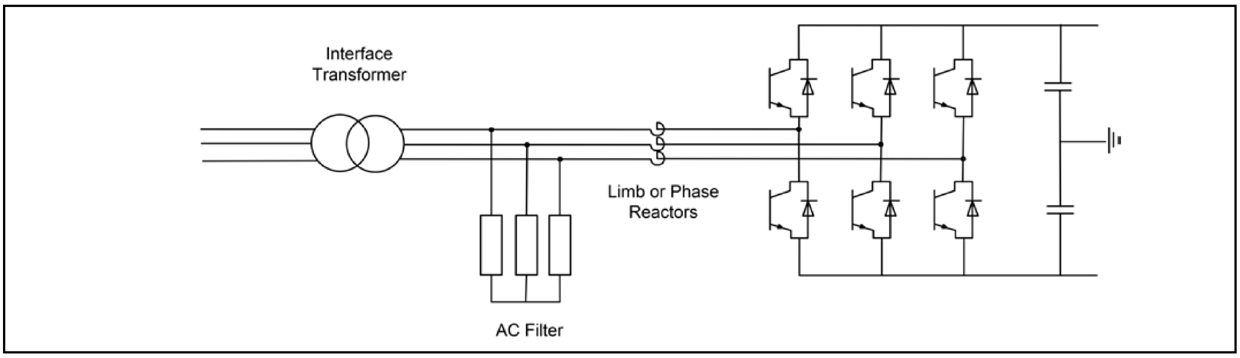

Figure 2: Basic representation of a VSC

to the load centre, but because of the variable characteristics of renewable power sources (wind for instance), power transmission also promotes a better integration of these renewable assets. The grid is therefore tasked to carry power in a more controllable manner and to combine renewable power generation with other sources. By this the grid can secure the overall region wide supply of the demand. The response to meet this new challenge requires a better integration of HVDC and HVAC systems.

2. New social demand on electric power production and transmission

There is no turning back from the course of decarbonisation of our society to avoid global climate change. This trend affects the way we live and produce goods, continuing to seek an improved quality of life in a more equitable society.

Power production is responsible for the largest part of greenhouse gas (GHG) emissions and thereby with more renewable energy sources being installed, and consequently the retirement of the old fossil-fuel fired stations, there will be a need for a remarkable expansion of the transmission systems, almost building it all from scratch. The type of expansion required is no longer only based on a few simple criteria related capability to supply the demand and stability. Now the requirements must go beyond that, and ensure the system will be able to operate in accordance with pre-established rules of security of supply, in which power corridors must have an intelligent power flow and be fully controllable by the operators. Such requirements will apply equally on the distribution side and at the transmission level. Because HVDC systems transfer power based on controlled switches, i.e. in principle controlled by software, there is less risk that the intermittency of the energy sources influences the operation of the system as it is the case of AC. This aspect also favors a larger participation of DC in future grid.

Another factor that is pushing the transformation of the power industry, and the HVDC system development in particular is the planning permit authorisations.

With this development, a new challenge is posed with overhead transmission lines, almost no longer being possible to install. The trend has begun and new installations of offshore and onshore transmission are practically only based on underground or sub-sea cables.

For the electrical operation of long cables, AC systems become rather complicated due to the reactive power compensation. For DC projects there is a heavy pressure to drastically lower the terminal costs. Hence the industry has been called upon to evolve and find new solutions to allow for simpler and more cost effective solutions for cable systems. This resulted in DC cables being built with extruded XLPE (cross-linked polyethylene) as opposed to mass-impregnated technology. In order to enable the use of XLPE cables, it was necessary that the previous technology, based on thyristors, which cannot be turned off by control action, would have to give way for an alternative based on transistors or more specifically IGBT devices, which are gate-turn-off devices. With this, the HVDC terminals of the cable ensure there are no polarity reversals on the cable insulation. The converters that operate like this behave as a voltage source, thereby called voltage source converters or VSC for short. The first prototype installation of a VSC converter scheme was put in service in Sweden in 1994 between Hellsjon and Grangesberg, using an existing AC distribution line. Since the prototype of this new breed of converters, much has been done and today they are based on modular-multi-level converter systems (MMC). As it is a fairly new technology, developed during the last ten years, it is still undergoing rapid development. New ideas on how to perfect different aspects emerge and are being explored almost on a daily basis.

With LCC technology the voltage change polarity at power reversal, while with VSC the current change direction

With LCC technology, valves conduct the DC current always in the same direction. In order to make a power reversal, the voltage must change polarity. The VSC systems always keep the same voltage polarity and the current can change direction for power reversals. Thus, the voltages to

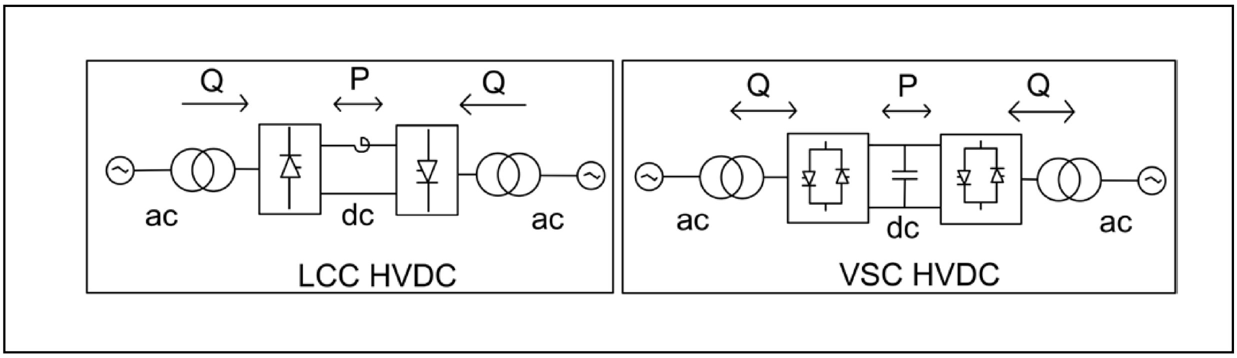

Figure 3: Salient features and major differences between the classic LCC HVDC and VSC [1]

which the transmission cable is exposed are better controlled and stay within a narrower range for the VSC schemes allowing both mass impregnated (MI) and XLPE cables to be adopted. This creates more offering and additional supply sources, resulting in a lower cost. With economies of scale, there should be further opportunities for lower costs.

The LCC converters always absorb reactive power at a rate of 50 – 60 % of the transmitted active power. A combination of converter firing angle control actions and external additional equipment is used to control the reactive power exchange with the connected grid. On the other hand, VSC converters can absorb or generate reactive power. Active and reactive power can be controlled separately.

The last 5 years have seen an intense activity to reduce electrical losses in VSC converters, which initially adopted pulse width modulation (PWM) to synthesise the AC voltages from a constant DC voltage. This method brought directly from industrial applications or traction drives, uses a high switching frequency compared to the line frequency of 50 Hz, and produce high switching losses. Due to the high losses, this concept was abandoned as all the major HVDC suppliers moved on to a modular multi-level converter (MMC) approach for which the switching frequency is much lower.

MMC technology is drastically reducing losses and harmonic distortion from the switching operation

The MMC technology is based on stepwise switching with much lower frequency and voltage amplitude jumps, combined with harmonic modulation in the synthesising AC voltages. Hence resulting in softer switching, lower losses and negligible harmonic distortion on the synthesised voltage.

3. Differences in transformer criteria between LCC and VSC

The HVDC transformers, converter interface transformers, or converter transformers for short, provide connection between the AC grid and the converter valve arrangement. The basic transformer function is partially the same as in the AC system, i.e. to connect two or more circuits at different voltage levels, whilst

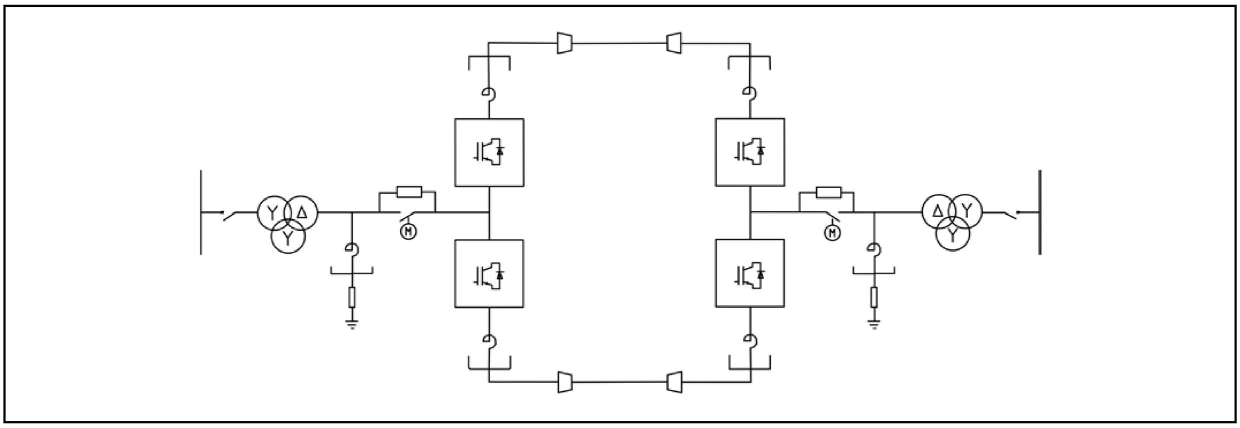

Figure 4: Functional scheme MMC VSC HVDC scheme in monopolar configuration [1]

HVDC transformers are integral in HVDC systems and provide multiple functions for the HVDC transmission system


[2]

allowing power to be transferred between them by magnetic coupled circuits.

Because the active power transmission in HVDC schemes is made on the DC side, the voltage necessary for the intended operation of the converters to conduct their switching functions is rarely the same as readily available on the AC grids. The system design engineering for a given DC transmission scheme will determine almost freely the transmission voltage to give the lowest cost for the DC cable or the DC overhead lines. The activity comprises a technical-economic study to minimise the present net value of the cost of conductors, transmission towers, insulators, construction, Right of Way, etc. - in summary, all aggregate aspects of the 'DC Line'. As part of the optimisation, the cost of Joule-losses in the transmission is also considered. The exception to the above is when the transmission is a back-to-back scheme, where the converter valves and transformers are the highest part of capital expenditure. In these cases, the maximum current of the semiconductor devices is fully used to minimise the amount of equipment. In those cases, limitation of valve side short-circuits could dictate a higher transformer reactance.

From the hints above, it should be clear that converter transformers are much more important for the transmission system than "just connecting the right voltage levels". They are in fact, an integral part of the HVDC scheme in order to provide the following:

1. Electrical separation (full galvanic isolation) between AC and DC sides, such that the earthing on the AC side and the earthing on the DC side are not the same. The earth electrodes on the DC side can be used as an integral part of the current carrying path, hence must be efficiently operated without suffering potential elevation from faults, for example on the AC side. The converter transformers' design considers a small leakage DC current to be conducted through the AC windings without giving rise to the saturation of the core of the converter transformers.

2. Elimination of harmonics which are caused by the rectification and inversion. The transformer connections of the valve side windings in a LCC scheme are typically used to create a 30°el phase-shift between two full wave six-pulse rectifier (inverter) bridges. This is easily accomplished by having one bridge fed by a set of Y-connected windings, whereas the other bridge in series is fed by D-connected valve windings. This forms a twelve-pulse converter, hence cancelling the characteristic harmonics of order 6n on the DC side voltage, and the side bands 6n±1 on the AC side currents. This will increase the order, and decrease the amplitude of the total harmonic generation by the conversion process. This simple solution saves much equipment and station footprint with the corresponding reduction in filter equipment.

3. The transformers participate in the control of the power transmission scheme by operating their OLTCs. The control of the voltage and current in an HVDC scheme is affected by the control angle ordered by the control software to the high voltage thyristor valves. In order to have constant control angles whilst minimising losses and reactive power, the transformers operate their OLTC under the HVDC control to adjust DC voltage and control angles. OLTC in typical LCC converter transformers may include more than 30 steps providing a wide voltage range (as wide as 40%). This is more than enough to compensate normal AC grid voltage fluctuations. It could even provide for temporary operation with reduced DC voltage to cope, for instance, with urgent situations of DC line insulator contamination by bush-fire or salt storms whenever it is deemed that in spite of adverse conditions the power transmission must remain in service.

4. Shield the converter valves from transient currents and short-circuit current.

Offshore wind connections drive the need to drastically improve power density in transformers

5. Provide accurate reactance for a perfectly balanced conversion process. As mentioned above, the transformers are crucial to achieve the cancellation of the low order characteristic harmonics. Therefore the transformer design and the actual measured voltage turns-ratio as well as consistency in achieving equal dispersion reactance on all individual transformers are common requirements for converter transformers.

6. Whereas transformers for classic HVDC with LCC technology must be built for the combined AC and DC stresses, the VSC interface transformers can be made without continuous DC voltage stresses by the choice of the HVDC scheme configuration. In most of the VSC systems built or under construction, the transformers feeding the converters are closer to a normal AC transformer.

4. The demand for renewable energy drives a need for higher power density of transformers

Offshore HVDC transmission systems are one of the fastest growing niches of power transmission today and will remain so for years to come. For offshore wind applications, the size and weight of the offshore platform is directly affected by the size and weight of the transformers. The relation "power/volume" and "power/weight", must be optimised in offshore platform topside applications, as they directly affect the total cost. For HVDC platforms up to 1 GW, three-phase transformers have been recommended to reduce volume and weight. Currently a series of 900 MW HVDC platforms are being built by Germany in the North Sea. All possible different transformer arrangements have been studied, in order to provide adequate HVDC transmission capacity even in the case one of the parallel transformer units being removed from service for repair.

Because of prevailing ambient temperature conditions, and the variable nature of wind power generation, with a capacity factor below 45%, an uprating of units can be considered. Hence, when one of the units is taken out of service, the HVDC interconnector could still run at 100% of nominal power for a limited period, whilst one unit is out for repair.

Rapid changes to the market demand due to renewable power generation, also put new requirements to transformer designs. Innovative transformer solutions are therefore more important than ever. Our recommendation to the transformers society is to look at further solutions that will boost the power and weight, volume and footprint performance of these transformers; solutions that also can be used in other applications. New development in base materials, cooling methods, development of sensors and intelligent transformer monitoring can support such development in a positive way. Transformers have played a central role in supporting HVDC so far, and can with engineering ingenuity become even more important when the society asks for sustainable energy solutions. We are simply asking the whole transformer engineering community to come up with more solutions to support a rapid development within this field.

References

[1] *CIGRE Technical Brochure 492 - Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other AC and DC Technologies – WG B4.46 – April 2012*

[2] Simon Villeneuve, *Transformateur du complexe La Grande.jpg*, http://commons.wikimedia.org/wiki/File:Transformateur_du_complexe_La_Grande.jpg, current 27.06.2014.

Authors

Andre CANELHAS, holds an Electrical Engineering degree from the Pontifical Catholic University of Rio de Janeiro. Andre started his career at Furnas and soon joined ABB, participating in the HVDC system design, system tests and commissioning for the Itaipu HVDC project. In 1984 he transferred to ABB Sweden, as system design, control and protection departments manager. Between 1992 and 1995 he was a project manager for the Kontek HVDC cable interconnection between Denmark and Germany. For his excellent performance he was awarded the "Project Manager of the Year" - 1995 by the Swedish Project Academy. Between 1995 and 1997, Mr. Canelhas worked in the project commercial team for the consortium between ABB and the Brazilian builder CBPO and later as the overall project manager technically responsible for the Bakun HVDC project. In 1997 he took the role of General Manager for ABB T&D Power Systems Division in Brazil. Andre worked for SIEMENS between 2001 and 2005 where he was responsible for the South American Projects Division. From 2005 to 2010 he worked for Alstom Grid and was responsible for HVDC and FACTS businesses worldwide. In 2010 he joined Siemens Wind Power in the UK. Currently Mr. Canelhas owns his own company supporting implementation of HVDC and FACTS projects. Mr. Canelhas has patented work, actively participates in CIGRE and IEEE and is author of technical papers on advanced electrical power systems.

Matti Stoor has 30 years of global experience from working with transformers as well as HVDC. During more than 17 years within HVDC, he was involved in design and development of HVDC control systems and later managed the HVDC control systems department and finally was General Manager of the Converter Technologies operation, covering LCC and VSC HVDC technologies in Ludvika, Sweden. Within transformers Matti has had many roles, where the later included heading ABB´s overall Chinese Transformer operations, as well as Global Business Development for Power Transformers. Matti is now running a business with focus on supporting clients in improving their holistic performance within the power industry. Matti holds an engineering degree in Control Systems, a Bachelor's degree in Business Administration and an MBA in International Business from Uppsala University, Sweden.