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Challenges in bringing UHVDC from ±800 kV to higher voltages

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SUMMARY

In the last decade, one of the major breakthroughs in HVDC transmission system has been the establishment of a new voltage level, i.e. ±800 kV. Already now, an UHVDC project of ±1100 kV is under construction with well justified economic advantages and technological solutions. This paper looks into the technical challenges to bring UHVDC from ±800 kV to higher voltage(s). It focuses on the technical challenges and possible solutions, based on and beyond what have been used today, even though some of them are only in the conceptual levels. With this perspective, the challenges and outcomes already encountered in the developing of the first ±1100 kV system is a good reference. The origin of the challenge is the need of more insulation to meet the increased voltage stresses. However, when arriving at the UHV level, nonlinear characteristics of the insulation strength result in other complexities. It should also be realized that in the process of the development, both for 800 kV and 1100 kV apparatus, not only voltage levels have been increased but also the current levels. The size of most of the apparatus in the system has become so large; it has become increasingly difficult to meet the mechanical and thermal constraints. To mitigating the combined stresses by insulation, mechanical and thermal effects, a holistic view is necessary. This is the key to the success of the new system with higher voltage levels. In an HVDC system, with regards to reliability, the overhead transmission line is often the weakest link in the whole system. Transmission line is considered to be the main obstacle for the wider application of UHVDC systems and for the further increasing of the system voltage beyond 1100 kV. Alternative solutions are warranted. Apparatus in the converter station have been and could be further developed with innovative solutions to meet higher requirement and even higher voltage level than 1100 kV. Among station apparatus, wall bushings for DC pole might be considered as the most challenging one, then come the converter transformers. As for the converter transformers, intrinsically, none of the mentioned challenges can be said to be impossible to develop beyond the limit that exists today, 1100 kV UHVDC. There are also and could have more alternative solutions for converter station design, if further development are required.

KEYWORDS

HVDC, UHVDC, Converter Transformer, Bushings, Converter valve, High Voltage Insulation, Converter Station, 800KV, 1100KV.

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1. GENERAL

In the last decade, one of the major breakthroughs in HVDC transmission system has been the establishment of a new voltage level, i.e. ±800 kV [1] [2]. The term of UHVDC (**U**ltra **H**igh **V**oltage **DC**) become realized after some 30 years since an HVDC system of ±600 kV has been in operation since late 80's. With the energization of first test station at 800 kV DC in Sweden in 2006 [3], 800 kV UHVDC system has evolved from transmitting 6 GW power to 10 GW, and, from system of two terminals to systems of multiple terminals [4]. Lines and converter stations of 800 kV have been built in various ambient conditions with altitude more than 2000 meters above sea level. The technology should be considered fully mature with over 10 transmission lines in operation and/or construction. And, already now, an UHVDC project of ±1100 kV is under construction with well justified economic advantages and technological solutions [5] [6].

On one hand, it could be still of interest to discuss the possible applications and economic feasibility of UHVDC systems with voltage level higher than ±800 kV or even higher than ±1100 kV. On the other hand, it is also of important to look into the technical challenges to bring UHVDC from ±800 kV to higher voltage(s). This paper focuses on the technical challenges and possible solutions, based on and beyond what have been used today, even though some of them are only in the conceptual levels. With this perspective, the challenges and outcomes already encountered in the developing of the first ±1100 kV system is a good reference.

The origin of the challenge is the need of more insulation to meet the increased voltage stresses. However, when arriving at the UHV level, nonlinear characteristics of the insulation strength result in other complexities. The size of most of the apparatus in the system has become so large, it has become equally difficult to meet the mechanical and thermal constraints. Mitigating the combined stresses by insulation, mechanical and thermal effects is the key to the success of the new system with higher voltage levels.

2. UHVDC TRANSMISSION LINES

2.1. Challenges

In an HVDC system, with regards to reliability, the overhead transmission line is often considered the weakest link in the whole system. The lines are designed to be able to carry the system current with relative low losses during the highest ambient temperature. These are to be structured to have an acceptable level of corona loss in both fine and foul weathers conditions. Ambient stresses such as atmospheric over voltage, pollution, precipitation, wind and earthquake; all have impacts on the insulation and mechanical strength of the overhead lines. It also has to be designed to have acceptable low level of impact on the environment in the form of, e.g. radio interference, audible noise, ground electric field including ion flow, and visual impact. Therefore, in many region, building new overhead lines are getting more and more difficult to be accepted. Even the regions where building over-head lines are possible, the challenges to build lines for UHVDC are severe.

The height of the tower for DC lines is determined by both the required line to ground distance and the length of the insulator. The size of the towers is determined by the line to tower distance and the mechanical requirement. The line to ground distance, is in many cases, dimensioned by the required acceptable level of ion-field at ground level. The insulator length is dimensioned by the pollution severity and lighting over-voltage. As an example in figure 1, the height of a tower for UHVDC ±800 kV line is of the order of 50 meters in ordinary conditions. The cross-arm spans around 40 meters for a horizontal bi-pole arrangement. The cross-section of the typical tower-foot is around 10×10 meters. For UHVDC ±1100 kV, the size of the tower may become some 30 to 40 % larger than the 800 kV towers. The cross-section of the tower foot may need to be increased by more than 40%.

Figure 1. DC lines of Xiangjiaba-Shanghai UHVDC 800 kV project of SGCC in China

Opposite to the overhead lines is the underground cable with solid insulation. It avoids all the challenges caused by the use of outdoor air as insulation. It encounters however other type of insulation and mechanical challenges. Commercial product of underground cable above 600 kV DC is not available presently.

2.2. Gases Insulated Transmission Lines

Between overhead lines and underground cables, there are the alternatives of enclosed transmission lines insulated by gases. The insulation gases can be of various types including clean air. Gas insulated stations (GIS) for DC systems have been developed, but adopted only for limited applications. For long distance transmission over various geological conditions the traditional design of GIS may not be an attractive solution. However, if the requirement on gas property is less stringent than that for GIS, the gas insulated transmission line may become available for long distance transmission.

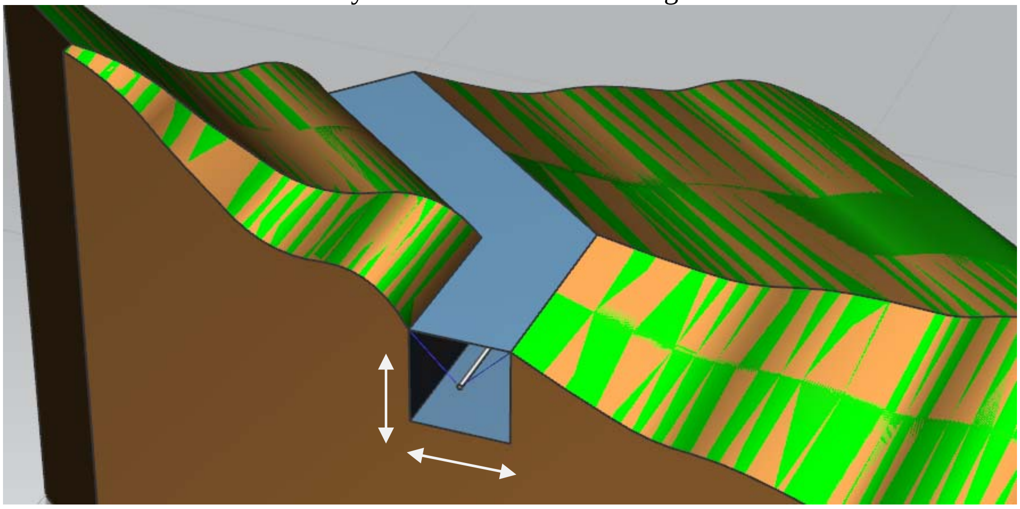

Figure 2. Pictured illustration of possible application of air insulated DC line inside a section of metallic enclosure

Assume that ordinary atmospheric air is used as insulation. The transmission line is suspended by two strings of insulators in V form from the upper corners of the rectangle metallic "container/enclosure", as in the pictured illustration in Figure 2. When carefully designed, the cross-section, determined by air clearances could be limited within 10 × 10 meters for UHVDC 800 kV for single pole with metallic return. As it has been reported earlier, with 33 mm/kV of USCD (unified specific creepage distance), a porcelain insulators string will be sufficient to withstand extremely high pollution level under relative humidity of 90%. Therefore, with an enclosed structure to prevent atmospheric precipitation, neither humidity control nor stringent pollution control will be necessary for the creepage design. The main task is only the air clearance design. With the same principle 15 × 15 meters cross-section could adapt UHVDC 1100 kV. In comparison to the size of the overhead lines, this alternative is not totally out of the proportion.

3. UHVDC CONVERTER STATIONS

3.1 Converter Transformers

3.1.1. The Challenges and the solutions

In the area of converter transformers, there have been rapid development even within the existing 800 kV DC technology. Following its introduction in the years 2008-2009, a constant incremental development has taken place. The two main areas of development have been power rating and the AC-voltage level to which the converter transformers are connected. The starting point for development was 6 400 MW transmitted on ±800 kV UHVDC from an AC network voltage of 500 kV AC in the Xiangjiaba - Shanghai project in China. The current benchmark is 10 000 MW transmitted on ±800 kV DC from AC-networks of 500-1000 kV AC in the Ximeng - Taizhou project in China. A sample of the intermediate steps are given in Figures 3.

Figure 3. From left to right: Xiangjiaba-Shanghai, Lingshao, Ximeng-Taizhou converter transformers.

The first technology step beyond 800 kVdc in terms of voltage was made in in the years of 2011-2012 when the technology development of 1100 kV UHVDC converter transformers was performed. Increasing the DC-voltage is synonym with handling an ultimate challenge in terms of the dielectric design of the converter transformer insulation. All insulation structures with the transformer was completely redesigned from fundamental principles, resulting in a range of novel solutions for winding insulation, DC-leads design and turret insulation. Given the sheer size of for example transformer bushings, as described in the following section, great care was also devoted to mechanical design challenges and production engineering.

The technology development phase of 1100 kVdc was crowned by the completion of the high voltage testing of the 1100 kV UHVDC converter transformer prototype in mid-2012. With the passing of all tests, it was proven that the converter transformer technology has established for the implementation of 1100 kV UHVDC converter transformer technology into a commercial project.

Figure 4. 1100 kV$_{dc}$ converter transformer prototype after passing all tests.

The project specification in mind when developing the original 1100 kV$_{dc}$ converter transformer technology was for a 10 500 MW transmission project. However, by the time the technology actually was put into use in the first commercial 1100 kV UHVDC project, the Changji - Guquan project, implemented by State Grid Corporation of China, the specification had changed to 12 000 MW. This was an important difference for the converter transformers since certain parts of the technology that have already been developed, have to be updated for a larger transmission current. Areas of the converter transformers impacted by this change was transformer bushings and its concerned insulation interfaces, but also the production infrastructure used for manufacturing of the converter transformers. In fact, all key production facilities for converter transformers were updated in one form or another, winding facilities, core stacking equipment, active part manufacturing, vapour phase drying capabilities, lifting capacity and test room capabilities are where upgraded to handle increased size, mass and test voltage. The final results of all these efforts boiled down to the successful type test of the of the converter transformer for the Changji station performed at the end of 2017.

Figure 5. 1100 kV_{dc} converter transformer for Changji station after type test.

3.1.2. Beyond existing technology for converter transformers

There has to be a major undertaking each time for a new voltage level for UHVDC transmission system being developed. Nevertheless, there are clear development and improvement potential beyond existing technology. In analogy with the development for 800 kV DC technology, even higher power levels for 1100 kV could be attempted.

Beyond this, the next step could be higher transmission voltage than 1100 kV. Key areas for such a development can be anticipated to be similar to those experienced when developing from 800 kV to 1100 kV, i.e., dielectric design of converter transformers, including transformer bushings, size of converter transformers, external insulation and mechanical design. Intrinsically, none of the mentioned areas can be said to be impossible to develop beyond the limit that exists today, 1100 kV UHVDC.

3.2 Bushings

3.2.1. Transformer Bushings

The increase of operating voltage levels to 800 kV UHVDC have already required manufacturers of transformer components such as bushings to take a step forward, and the next step up to ±1100 kV have added additional concerns for many design approaches. Not only the higher voltage level pushed clearance requirements upwards, affecting axial dimension of bushing, but also the diameter of core and insulators has increased. The increase of overall diameter is also due to larger conductors to handle the increased current rating.

The major design steps for transformer bushings for the converter valve windings have been focused on meeting the higher operating and test voltage levels for dc voltages, as well as the design of current conducting systems with sufficient margins. This applies in particular for the bushing installed at the highest position in the valve groups. The large bushings have air side corona shields designed to match the bushing and to reduce the stress in the high voltage end as well as keeping stress in air below level initiating breakdown. The current conductor achieves a larger diameter, which together with larger bulk of core defines the overall diameter, while voltages, both test - as well as operating voltage - also governs diameter, but primarily the length. The bushing on the highest voltage position has therefore initiated expansion of manufacturing resources of composite insulators. Located indoor, as in most of the cases today, no pollution related issues need to be worried. Air clearances in the valve hall are determined by over-voltage.

After reaching a conceptual design to enable the new voltage and current levels, verification from a mechanical point of view, including seismic requirements is performed. Besides evaluating the bushing itself, the converter transformer is studied to establish the amplification character of the ground acceleration the bushing is subject to.

3.2.2. Wall Bushings

Wall bushings are stand-along apparatus often stressed by both indoor and outdoor conditions. The gas insulated wall bushings with silicone rubber hollow-core insulator was successfully applied 20 years ago at 400 kV DC. With the same concept, application on UHVDC 800 kV has been successfully implemented 10 year ago. Today wall bushing for UHVDC 1100 kV has been developed and is ready to be installed. With the increase of voltage level, the terminal to terminal length of the bushing has also been increased from ~19 meters for 800 kV to ~26 meters 1100 kV, see figure 5.

Figure 5. 1100 kV UHVDC wall bushings at test set-up.

Significant developing efforts have been made during the way not only on voltage levels but also in current levels. The current level has been increased from 1500 A DC to 6250 A DC. The increase of current has also affected design of connectors for the wall bushings from two conducting leads to the later installations often featuring up to six or eight individual sub-conductors of a bundle conductor.

The length of the wall bushing is pushed longer by both the clearance requirement for the indoor part and also the creepage requirement for the outdoor part. Although supported by successful operational experience, the conservative level of 43 mm/kV have often being questioned. With such a long and slim body, the limitation factor for further increase system voltage is actually the mechanical design. A design that fulfil the seismic requirement will also be challenging. Other alternative solutions need to be explored.

3.3 Converter Valves

As the heart of the HVDC system, converter valves have been built by modulated structures. To increase the voltage level is to increase the number of thyristors connected in series. The increase of system voltage has little impact on the design of a single valve. The only difference between a single valve within a 500 kV DC system or an 1100 kV DC system will be the design of the external screens.

The design of external screen dictate in a great deal the size of the valve-hall. With the increase of voltage level and the non-linear characteristic of the insulation, to keep a reasonable size of valve halls, the improvement for valve screens is necessary. This is achieved by utilizing the dielectric strength of quasi-uniform, or slightly non-uniform gaps. Carefully designed experimental studies combined with electric field simulation are used to understand both the effects of small field distortions and the surroundings structure on the screen system. Such knowledge cannot be obtained just by standard type tests. Shown in figure 6 are the photo's for breakdown tests and type test (withstand tests) of the converter valve designed for 1100 kV UHVDC system.

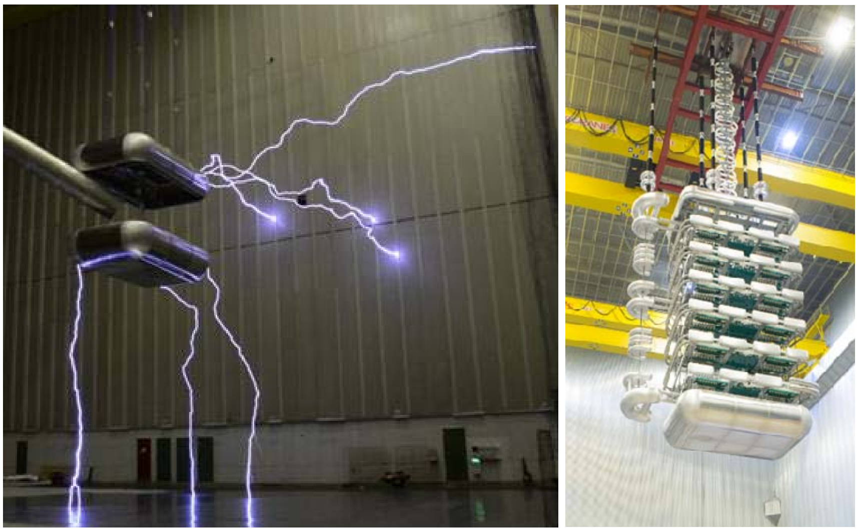

Figure 6. Breakdown test and type test of 1100 kV converter valves.

3.4 DC Yard Apparatus and DC Station Layout

3.4.1. Challenges

Similar to overhead transmission lines, DC apparatus placed outdoor have to face the combined effects of ambient conditions and voltage stresses. Ambient conditions related to pollution have been a severe issue especially for DC systems. Today with the superior performance under polluted conditions, the wide application of silicone rubber insulator has reduced the DC pollution issues into a close level as for AC systems. For UHVDC, challenges appears from the needs for very long insulators. For 800 kV, the insulator length have been controlled to be about 11 meters. For 1100 kV, the insulator length would have arrived at about 18 meters if solution with indoor DC yard have not been chosen. An inflationary spiral may be created between the length required by insulation and the diameter required by mechanical strength.

Other ambient conditions have strong impact on the design are the altitude and seismic activities. From the aspect of clearance, the altitude effects are more pronounced for shorter air gap than for long air gaps, therefore it is not a specific UHVDC issue. The effects of seismic level on the other hand have stronger impact on UHVDC than HVDC system on the long insulators.

3.4.2. Alternatives for Valve and Valve Hall

For valve and valve hall, the solution of "outdoor valve" has already been used for DC voltage up to 600 kV, figure 7. Such solution has long been considered as suitable for UHVDC application especially with the consideration of avoiding the very long wall bushings. Valves are installed inside several enclosures with air insulation. These encloses are in turn cascaded in series at different potential and insulated from ground by post insulators. By this way, a large valve hall can be avoided and also the long wall bushings. The design difficulties of wall bushing have been though transferred to post insulators.

There could also be a combination of valve hall solution with “outdoor valve” solution. As an example, the valve hall will be built for accommodate voltage up to 800 kV. Outdoor-valves could then be used only for voltage levels between, e.g. 800 kV and 1100 kV.

Figure 7. Outdoor valves.

3.4.3. Alternatives DC Yard Apparatus

For many of the sensitive apparatus, when installed inside an indoor DC yard, will reduce difficulties in design. For 800 kV UHVDC system, both indoor and outdoor solution have been realized, figure 8. Although a large hall is needed, when considering the effects on total project reliability, there still advantage to build such halls in place with exceptionally severe ambient conditions. For the coming 1100 kV UHVDC project, to ensure a high reliability, indoor DC yards will be built for both sending and receiving stations to accommodate apparatus at 1100 kV pole voltage, similar to as used in North-East Agra multi-terminal UHVDC project in India [4]. See figure 8.

Figure 8. Indoor DC yard of an 800 kV UHVDC project.

4. CONCLUSIONS

Looking back in the development of the UHVDC system from 800 kV to 1100 kV, many challenges have been met and successfully solved, fulfilling the need of respective project. In general, transmission lines are the main obstacle for the wider application of UHVDC 1100 kV and for the further increasing of the system voltage. Alternative solutions are warranted. Apparatus in the converter station have been and could be further developed with innovative solutions to meet higher requirement and even higher voltage level than 1100 kV.

Among station apparatus, wall bushings for DC pole might be considered as the most challenging one, then comes the converter transformer. It should also be realized that in the process of the development, both for 800 kV and 1100 kV apparatus, not only voltage levels have been increased but also the current levels. A holistic view is necessary to be able to meet all challenges. The mechanical and thermal constraints become in fact the main challenge instead of insulation design.

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