Paper presented at INMR 2015, 18-21 October, Munich, Germany 2015

Design Principles for External Insulation at UHVDC Converter Stations up to 1100 kV

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SUMMARY

External insulation is one of the critical design aspects for HVDC equipment in converter stations. This is especially the case for UHVDC systems. The basic design principal for such a system with energy transmission capability up to 10 GW is to achieve a superior reliability. In this report, a brief overview on the related issues especially those issues that are often discussed in this area is given based on the R & D results, design and operation of UHVDC systems. The issues addressed covers the ambient conditions, type of insulators, dimensioning of the air clearance, corona and electric field in the converter stations.

As the conclusion of this overview, it should be realized that the superior reliability can only be achieved by:
1. Utilize the knowledge and operation experience from existing HVDC system;
2. Identify and meet the new challenges with the increased voltage levels;
3. Balance the requirement for insulation and other constraints in the design.

KEYWORDS

External insulation; HVDC; UHVDC; Insulators; Air Clearance; Corona; electrical field; Testing

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INTRODUCTION

External insulation is one of the critical design aspects for HVDC equipment in converter stations. This is especially the case for UHVDC systems. The basic design principal for such a system with energy transmission capability up to 10 GW is to achieve a superior reliability.

Although from insulation point of view, voltage level is the main concern. However, with the increase of voltage level and the increase of equipment size, other constraints such as the mechanical strength and thermal effects become more of significant in the design consideration. Some effects, such as the effect of multiple gaps, become more critical for UHVDC. Even some of the design practice for personnel safety used for lower voltage level need to be reconsidered.

External insulation is a wide area which includes insulation design for air clearance, corona shielding, and insulators for both indoor and outdoor atmospheric conditions. This report, based on the R & D results, design and operational experiences of UHVDC systems, provides a brief overview on the related issues especially those issues that are often discussed in this area.

CRITICAL ISSUES ON EXTERNAL INSULATION

Ambient conditions

a) <u>Site conditions</u>
The site pollution severity of a planned converter station could be estimated by different methods [1] [2]. Since there are already many HVDC systems in operation under different site conditions, an effective way is to study the pollution effects on those existing DC systems. Another method is to set-up a test station near the location of the planed converter station [3]. For UHVDC system, it is more importance to get an accurate estimation of the site pollution severity, since the decision made base on this will have a significant impact on the reliability and also on cost of the project.

Other conditions that are of importance for the insulation design are the wind speed and the seismic requirement. These parameters will determine the mechanical requirement for equipment. Such requirement is constraint for insulation design [4].

b) <u>Indoor conditions</u>
In a converter station, some equipment is, in most cases, located indoor, such as the converter valves. Other equipment is often located outdoor but can also be installed indoor i.e., inside the so called indoor DC yard [5] [6]. Although the indoor condition is less complicated than that of outdoor, it is still influenced by the ambient air with different temperature, humidity and different level of dust accumulation. These parameters of ambient need to be defined and controlled.

c) <u>Selection between indoor and outdoor DC yards</u>
For HVDC system, the indoor DC yard is sometime build for the extreme site pollution severity or for the stringent requirement of compact design [4]. For UHVDC system, the length of the equipment has arrived at the critical value that the mechanical integrity of the equipment is at critical level. Considering the large amount of energy transmitted, indoor solution may become attractive. A decision like this requires a thorough study and comparison of different alternatives [5]. In Figure 1, photos of a 500 kV indoor DC yard and an 800 kV outdoor DC yard are given.

(a) (b)

Figure 1, DC yards: (a) inside view of a 500 kV indoor DC yard;
(b) Outdoor DC yard of XS800 project of SGCC

Type of insulators

a) Surface materials

For the simplicity and mainly from the pollution performance point of view, IEC has divided the surface characteristics of insulator into HTM (hydrophobic property transferable material) and non-HTM [1]. HTM includes mainly insulators with silicone rubber surface. Non-HTM includes insulators with surface that cannot maintain or recover its hydrophobic property after being covered with pollution. With today's technical development, almost all insulators used in UHVDC system are with HTM surface.

For the discussions related to the advantage and disadvantage of silicone rubber insulators made by different types of silicone materials and with different types of manufacture techniques, they were often in generalized term and could be misleading. Any such discussions should need to be justified with the support of a comprehensive study of the operation experience, such as in [7].

It is also inaccurate to generalize the hydrophobic property of an insulator by just using HC (hydrophobicity class) levels. HC measurement is a simple and quick method to get a rough estimation on the surface status. However, report from on spot HC measurement shown that the HC levels were, in most cases, different at different parts of an insulator and changed rather quickly with the ambient conditions [7]. The expected pollution performance of an insulator cannot be obtained just with a few HC measurement.

b) Linearity

For 800 kV DC, the relationship between dielectric strength and the length of the station post insulator under artificial pollution had been confirmed to be linear when the applied pollution was higher than 0.05 mg/cm^2 of SDD [8]. For lower SDD levels, the relationship was slightly non-linear. This was obtained under the condition that the test object was porcelain insulators with uniform pollution layer. For higher voltage than 800 kV DC, to perform such tests will become difficult. One of the difficulties is that the fog applied in test chamber tend to be non-uniform which will lead to a partial wetting of the insulator. The UHVDC systems have and will be designed with the assumption that the linear relation remains even for higher voltage levels [4].

c) <u>Shed profile</u>

The importance of the insulator shed profile to the performance under various types of wetting conditions have been established although it was difficult to represent the natural pollution conditions in laboratory tests [1] [2] [9]. For DC application, to avoid the bridging of the sheds by partial arcing, a relative large shed spacing than what is used under AC application are necessary [2] [9]. This is especially the case for UHVDC system, with its large insulators. This principle, established for porcelain insulators, have also be applied to insulators with HTM surface [2].

Based on the same profile principles, the use of spiral or helix formation of sheds is related only to the manufactory techniques. For station insulators with a large diameter and for insulators with HTM surface, it is evident that with the same profile parameters, sheds formed by helix technique have given satisfactory performance [10].

d) <u>Creepage distance</u>

Although it had been successfully tried earlier [11], it was in China the researcher and utilities adopted in large scale the principle of using shorter creepage for HTM insulators than that for porcelain insulators and with successful experience in real operation [12]. This principle made it possible to produce equipment for UHVDC applications. Such principle may be applied to most of inland conditions. For some extreme conditions with frequent appearance of wet pollution, e.g., very close to the sea, restraint may need to be exercised with consideration on the risk of ageing [2].

For indoor conditions, with the absence of the most common wetting processes, such as rain, fog and snow, much shorter creepage than that for outdoor may and have be used, even though dust may appear indoor. In most of cases for indoor conditions, creepage will not be the dimensioning parameter [5].

For insulators installed in an horizontal position, such as the wall bushings, shorter creepage than that for vertical insulators may be used because of the more effective nature washing and less risk of water bridging of sheds [9]. This fact that a shorter creepage may be used is especially true for wall bushings with silicone rubber sheds. The HTM surface make the wall bushing insensitive to uneven rain. Operation experiences of wall bushings with silicone rubber sheds worldwide support such a conclusion [13].

For apparatus with controlled internal voltage distribution, the dynamic change of external voltage distribution due to different weather conditions need to be well considerate in the design. The tendency of using very long creepage may worsen this situation.

The main constraint for using longer creepage distance in UHVDC system is the requirement on mechanical design. From system reliability point of view, mechanical safety weights more than the flashover risk of external insulation. A good balance should be achieved between the requirement on external insulation and the negative effect of a too long insulator on its mechanical strength.

e) <u>Testing</u>

To achieve a better understanding of the relation between stresses and strengths of the external insulation, numerous laboratory tests have been carried out which provided valuable knowledge for the design of external insulation [9]. However, on the other hand, laboratory test cannot fully represent the natural and operation conditions, such as the complicated conditions like pollution performance. Therefore, to rely on some artificial pollution tests to determine the “go or no go” for an external insulation design is highly inaccurate [2]. The accuracy will be even worse off when HTM insulators are judged by such a test. Therefore, it should be concluded that testing with R & D as the aim is beneficial for the design, while testing, e.g., in form of type tests, for verify a design may often be misleading. For UHVDC, even the availability of the test facility to test the full scale equipment becomes a difficult issue.

Determination of air clearances

a) *Multiple gaps*

By multiple gaps, it is referred to the situation that one high voltage electrode facing several grounded electrodes, e.g., walls, see Figure 2. This is not the same situation as the parallel gaps. For parallel gaps it is referred to the situation that several high voltage electrodes stressed under the same voltage and each facing a ground electrode and acting independently. For parallel gaps, there is well established way to account the changes in breakdown statistics in comparison to a single gap [14]. However, for multiple gaps, it has to be handled by well-coordinated insulation design. For UHVDC, with the long air clearances in the main gap, it becomes difficult to exclude the influence of other grounded electrode to the main gap [15].

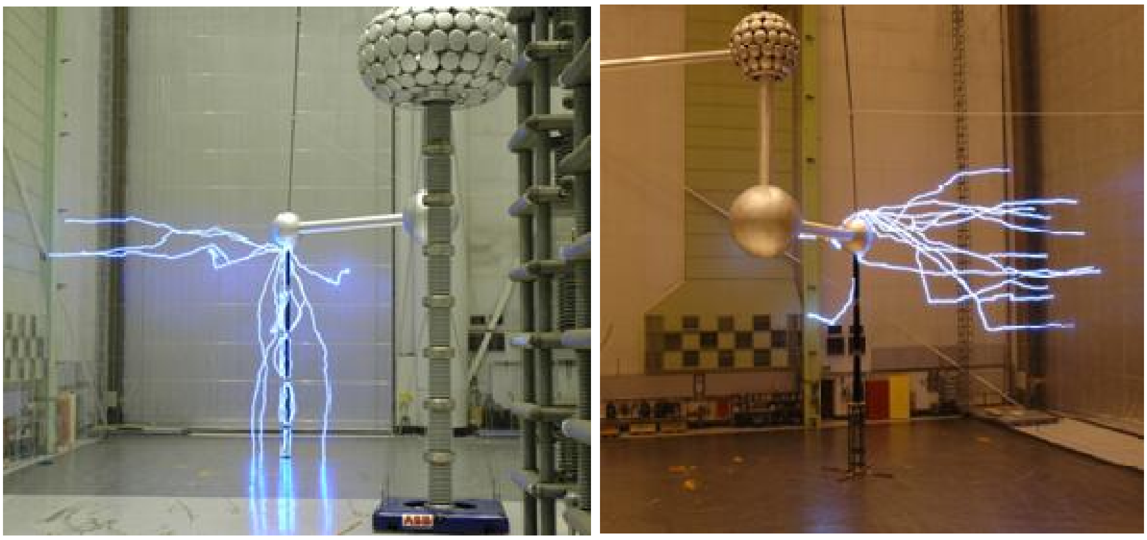

Figure 2, Influence of walls on the breakdown trajectories.

b) *Saturation and damaged electrode*

The switching impulse is, in most cases, the dimensioning stress for air clearances in HVDC stations. It has been well established that under switching impulse, the relationship between dielectric strength and the gap distance is non-linear and it saturates rater quickly [16]. This is especially the case for “rod-plane like” gaps with large electrodes [17]. For such gaps, with large electrode, it saturates even fast than the rod-plane gaps. Therefore, the improvement achieved by an increase of the radius of the electrode reduces quickly with the increase of gap distance. This makes it necessary to improve the electrode each time the voltage level increase. Otherwise, the clearance has to be determined as that for a rod electrode.

Furthermore, any slight “damage” appeared on the surface of the large electrode will cause a drastic reduction of the dielectric strength [18]. For outdoor conditions, the combination of rain water with pollution drifting from the surface of electrode will make most of the air gaps behave like with a rod electrode [19] [20]. For indoor conditions, perfect electrode may also not be assumed. In this case, installation structures like the head of screws will also “damage” the electrode. Insects may appear indoor which may also cause unexpected breakdowns [21]. All these factors need to be included in the insulation design.

c) Safety distance

The other effect of the multiple gaps situation is the breakdown trajectory may extend its self to research other grounded electrode at a much longer distance from the main gap. This makes the “safe area” disappears in the vicinity of the main gap. Traditionally, for a lower voltage level, corresponding to 500 kV AC system or lower, it was believed that with a metallic pedestal of some 2.5 meters, it will be safe for the station personnel to access the substations even during operation. However, for UHVDC system, the arcing distances of insulators will be in the range of 8 meters and above. The probability of a breakdown takes place between the top electrodes to the ground will be increased [22]. Working during operation under a pedestal of 2.5 meter shall not be considered as safe for station personnel.

It should be considered that a safe distance shall have zero breakdown probability, i.e., with a distance that is evaluated with a margin of 5 sigma’s from the U_{50} [14] [23]. This criterion should apply only if in extreme cases that a person must come in the DC yards during operation. The other measure would be to build a safe corridor shielded from the arc of an eventual breakdown. Further study on the safety measures becomes an absolute necessity.

d) Testing

For the developing of products for a new and higher voltage level, laboratory experiments is a necessary tool. Insulation design is based on the principle of probability. The probability of the failure may be investigated with laboratory experiments using test procedures like, e.g., the up-and-down procedure. The up-and-down procedure is an effective and relative accurate procedure for the determination of withstand or breakdown probability. Various withstand procedures with small number of breakdowns cannot give the same level of accurate unless a great number of voltage applications will be made [24].

It is clear, on the other hand, equipment made of both self-recoverable and non-recoverable insulation cannot withstand many breakdowns. A balance must be researched that, on one hand, a reliable product will be developed and, on the other hand, not too many test objects will be destroyed. Although compromise are necessary, it is anyway not sufficient to justify a new design by only performed a standard withstand type test.

Computer modeling is in this case a useful alternative. Combined with laboratory experiments, computer modeling of the breakdown process provides deep insight on this complicated phenomenon. From engineering point of view, although modeling techniques developed today may still not be so handy as design tools, it is a power tool for simulate various situation that may not all be simulated in laboratory [25]

For test on self-recoverable insulation, there have been challenges when testing under UHVDC voltage level. It have been observed that, discharges or even breakdowns may appear on other part of the test circuit instead of the test objects. Such discharges and breakdowns should be avoid by modifying the corona shielding of the test circuit. To facilitate the observation of the discharges, digital cameras with a photo acquisition system have been used [15]. For each voltage application, photos over the test circuit from two different angles were taken simultaneous with the voltage application and immediately available for inspection in the control room. This makes it much easier for the researchers to decide on how to proceed with the voltage application.

DC corona and field in station

For indoor equipment and bus works, the design should be aim to be corona free. Although dusts in the air, charged by DC voltage, maybe accumulated to the surface of the electrodes, such effect should have been taken into consideration in the design [26]. For a corona free design, the electric field will only be the geometric field and can be calculated without considering the ion flow.

For outdoor conditions, the equipment and the bus work are conventionally designed to be corona free in fine weather and when new. It is unrealistic to design for corona free for outdoor conditions. Ion current appears when corona discharge presents. However, it should be remembered that a converter station with high voltage equipment and bus work is not a public area. No people should to be present there in ordinary conditions. Therefore, the criteria for ion-fields under DC transmission line should not be applied here.

CONCLUSIONS

The basic design principal for a UHVDC system with energy transmission ability up to 10 GW is achieve a superior reliability. This can only be achieved by:

1. Utilized the knowledge and operation experience from existing HVDC systems.
2. Identify and meet the new challenges with the increased voltage levels.
3. Balance the requirement from insulation and other constraints.

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