External Insulation Design of Converter Stations for Xiangjiaba-Shanghai ±800 kV UHVDC Project

[1]Dong Wu, [1]Urban Åström, [1]Gunnar Flisberg, [2]Zehong Liu, [2]Liying Gao, [2]Weimin Ma, [2]Zhiyi Su

***Abstract*--External insulation is one of the critical aspects in the HVDC equipments and converter station design. Especially for UHVDC converter stations, the long creepage and clearance required has significant impact on the equipment and station design. The external insulation design of DC yard, valve hall, and for converter valves is presented. It is the intention of this report to review and summarize the work that has been done and the decisions that have been taken to the benefit of further work and design of new projects.**

***Index Terms*-- UHVDC, External Insulation, Air Clearance, creepage distance, converter valve, Insulators.**

I. Introduction

External Insulation is one of the critical aspects in the HVDC equipment and converter station design. Especially for UHVDC converter stations, the long creepage and clearance required has significant impact on the equipment and station design [1]. To be successful in the design, close cooperation between the utility, who has the best knowledge on the site conditions, and the supplier, who has the ability to optimize the equipment to fit the site conditions, is invaluable. The experiences of Three Gorges-Changzhou (3GC), Three Gorges-Guangdong (3GG), and Three Gorges-Shanghai (3GS) ±500 kV HVDC projects are evidence of such successful cooperation [2-6]. Today, the design of Xiangjiaba-Shanghai ±800 kV (XS800) UHVDC project has passed many critical milestones. All equipment has passed the type tests and has been installed. It is the intention of this report to review and summarize the work that has been done and the decisions that have been taken to the benefit of further work and design of new projects.

II. Stress on External Insulation

This project is the first 6400 MW UHVDC project with valves equipped with 6'' thyristors. The reliability of such a project is of the highest priority. Therefore, in this project, pole voltage of 800 kV DC is supported by two 400 kV 12-pulses valve groups in series. These two groups are installed in separate valve halls (called HV and LV halls) and each of them can operate separately (when the other is out of service) see Fig.1.

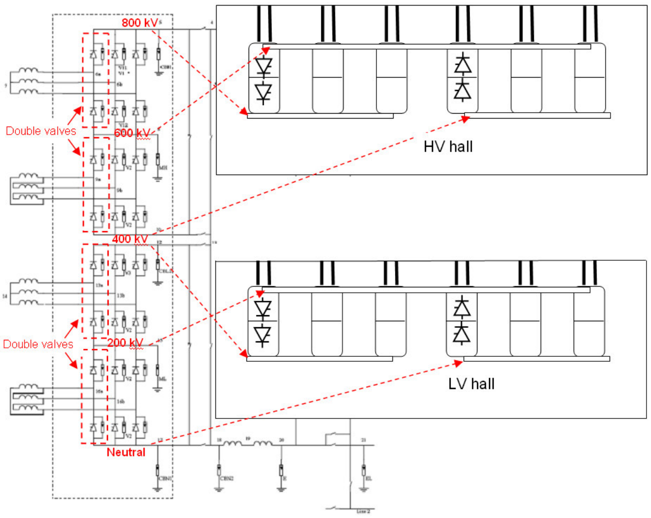

Fig. 1. Converter valve connection, arrester protection and layout in valve halls

Until now, for HVDC projects, the external insulation has been designed with deterministic method, a conservative approach for insulation coordination. The maximum voltage stresses are obtained through an insulation co-ordination study. The terms of lighting impulse protection level (LIPL) and switching impulse protection level (SIPL) are used to specify the maximum over-voltages. The levels of over-voltages at and between different points of the circuit are controlled by the arresters, as illustrated in the circuit diagram in fig. 1. Predetermined safety margins of fixed values are introduced for each typical waveform, typically 20% for LIPL and 15% for SIPL. They are added to cover possible discrepancies such as uncertainties in system studies and variations in quality of production. The results are the required withstand voltages in the form of standard lightning and switching impulse referred as, e.g. lighting impulse withstand level (LIWL) and switching impulse withstand level (SIWL). Supported by operational experience, these voltage levels can be used without correction for the design of insulation for altitudes up to 1000 m.

Pollution, rain, and the variation in ambient conditions are

[1]Dong Wu, Urban Åström, and Gunnar Flisberg are with ABB HVDC, Sweden. (e-mail: dong.wu@se.abb.com)
[2]Zehong Liu, Liying Gao, Weimin Ma, and Zhiyi Su are with State Grid Corporation of China (SGCC), P. R. China

also stresses to external insulation. The external insulation shall be designed to withstand the combination of these stresses under various voltage stresses.

For a specific insulation point, it is often the case that there is one type of stress, among the various combinations of stresses, that gives the most onerous condition. If the insulation is designed to withstand such a condition, all other conditions can be automatically satisfied with good margin. This is the dimensioning stress. It is important to identify this stress for insulation design.

III. DC YARD

A. *Site pollution severity and creepage requirement*

Based on site condition study and experience from several earlier HVDC projects in China, the site pollution severity has been determined. The pollution-severity for design is specified for both converter stations as in table I.

TABLE I
SITE POLLUTION SEVERITY

Insulator type	Design ESDD mg/cm^2
AC standard cap-and-pin	0.06
AC station post	0.03
DC station post	0.064

Note: The NSDD value is 5 times of the ESDD value.

As the base for the design, the required creepage distances for porcelain insulators are also given, in table II.

TABLE II
CREEPAGE DISTANCE FOR DC

Equipment		Creepage in mm/kV
Station post		54
Vertical bushings	$D_{average} \leq 400$ mm	57
	$D_{average} \leq 500$ mm	59
	$D_{average} \leq 600$ mm	61
Wall bushings		60

Supported by many years successful experience, silicone rubber insulators can be used with shorter creepage, e.g., 75% of that required for porcelain.

B. *Insulators shed profiles*

The length of an insulator is determined by the creepage distance and shed profile. To use suitable shed profile has been proven to be very important for the performance of insulators under DC, especially for vertical insulators with large diameters [7]. For porcelain station insulators under DC, there is a lot of experience on the suitable shed profiles. For silicone rubber insulators, however, the experience on the suitable shed profile under DC is still limited.

To facilitate the design of DC yard for the UHVDC projects, recommendations on the suitable shed profile for silicone rubber station insulators have been given by a joint group of experts from utilities, research institutes, universities, and the supplier [6]. To give such recommendations, experience form HVDC systems with voltage up to 600 kV has been reviewed. The risk of temporary reduction of the hydrophobic property of silicone rubber insulators has been taken into consideration. These recommendations have then been adopted by this project as requirement for vertical insulators of an alternating profile:

- Spacing/overhang ≥ 0.9;
- Spacing ≥ 65 mm (for vertical position);
- Difference between overhang of the larger and smaller sheds ≥ 20 mm;
- The sheds upper inclination angle >10^o;
- The sheds under inclination angle >3^o.

For insulator that is installed in a near horizontal position, e.g. the wall bushings, and insulators that have a smaller diameter, e.g. the arrestors and insulators for capacitor cans, their shed profiles can be different from the requirements.

C. *Station post insulators*

To withstand the specified pollution-severity and fulfill the creepage as well as the profile requirements with porcelain insulators, the porcelain insulator will need to be longer than 14 meters. Such an insulator is difficult to produce, mechanically unreliable and economically expensive. Today, all apparatus in a DC yard can use silicone rubber housing. With a shorter creepage distance than porcelain, the lengths of these insulators are still within the production limitation. Only the station post insulator remains to be made of porcelain. To choose an alternative solution for station post insulator becomes a critical issue in DC yard design.

There are, at this moment, no mature products of station post insulator with silicone rubber housing for HVDC application. However, four types are available as prototype products with no real operational experience. They are:

- Hollow-core silicone rubber insulators filled with foam,
- Hollow-core silicone rubber insulators filled with insulating gas,
- Solid-core silicone rubber insulators with glass-fiber and epoxy as core material,
- Hybrid insulator, i.e., porcelain core with silicone rubber housing.

All these insulators have its merit and drawbacks. Technically, the hybrid type seems most promising while the gas filled type seems most mature. Economically, the gas filled is probably the cheapest alternative. However, with the gas filled type, the station operators would have to face quite a few more checking points for gas pressure during maintenance.

It is also important to pay attention to other constraint involved in the comparison, e.g., the mechanical requirement such as the rigidity of the post insulator. Station post insulators will support the bus-bar and other equipment that is suspended on the bus-bar. E.g. for this project, the dry smoothing reactors with a weight of 60 tons will be supported by several post insulators. Equipment in the station is connected by hard or soft bus-bars. The rigidity of these post insulators has impact on the station design. The mechanical characteristics of the whole station during strong wind and earthquake need to be considered. Considering this project is the first 6400 MW UHVDC project and the short delivery time plan, a prudent approach has been taken by not applying these prototype products in this project.

D. Indoor DC yard

One solution for meeting the unconventional requirement on external insulation is to build an indoor DC yard and putting all insulators indoor. There are many advantages in building such a hall, supported by the good experience of Zhengping station in 3GC project [5]. There are, however, also several limitations. Especially for UHVDC project, the required air clearances will be very long, due to the non-linear relation of air clearance and switching overvoltage. Therefore, the hall of indoor DC yard in a UHVDC project will be unconventionally large.

In order to make a comprehensive comparison, including economical aspects, a conceptual design was made for both indoor and outdoor arrangements. Equipments for both conditions were identified and installed in a 3-dimensional CAD layout; Fig. 2. It was found that the indoor design will lead to an increase of the total project costs, maintenance costs and auxiliary power consumption. Such cost increasing is not fully justified to meet the difficulty in the design and production of station post insulator. For this reason outdoor design has been adopted by this project.

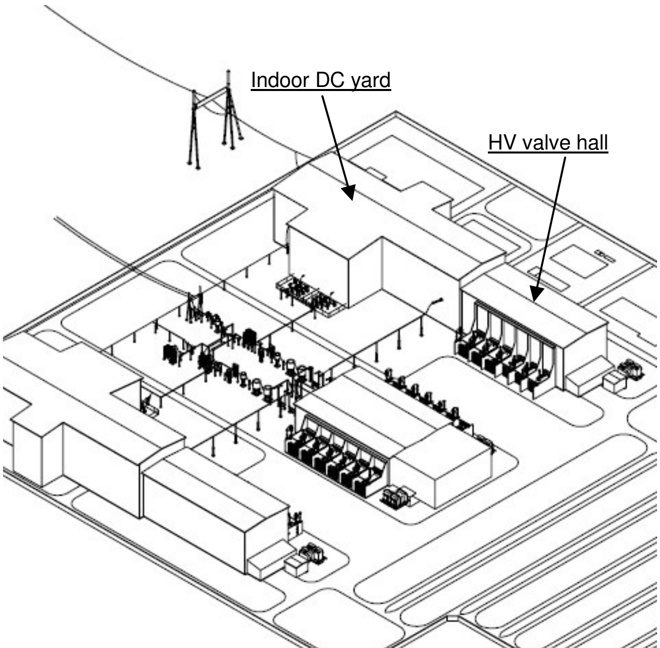

Fig. 2. Layout of converter station with indoor DC yard

E. Coated porcelain insulators

The application of hydrophobic coatings on porcelain insulator is a well proven solution. Both the use of RTV coating and silicone grease has been successful with worldwide experiences over many years [8]. The drawback of using coatings is that the coatings may need to be reapplied in a few years time depending on the types of the coatings and the site conditions. Traditionally, this solution was considered as a non-permanent solution and was not accepted as a design alternative. However, as it has been discussed in previous sections, the critical insulator in the context is the station post insulator. Flashover statistic from converter stations worldwide has shown that this type of insulator has very low appearance in the flashover statistics [8]. The maintenance effort for the limited number of station post insulator is small in comparison to other alternatives.

After thorough comparison with all the above mentioned alternatives, it was determined that porcelain insulators with RTV coating should be used as post insulators at 800 kV pole level with a shorter creepage distance than specified in Table II. The total length of the insulator is therefore reduced to 11 meters, resulting in a significant reduction in the difficulty levels of design and production of the station post insulator. Now, these insulators have passed the mechanical type tests and been installed at the converter stations.

Fig. 3. Outdoor DC yard at Fengxiang station, XS800 project of SGCC

IV. VALVE HALL

A. Design voltage and conditions

The dimensioning stress for air clearance is switching impulse voltage. As an example, the specified over-voltages at DC 800 kV pole in, e.g., Fengxian station are:

- LIWL=1800 kV, with a margin as high as **29%**, i.e., LIPL=1397
- SIWL=1600 kV, with a margin as high as **18%**, i.e., SIPL=1356 kV.

If a rod-plane gap structure is used, for the LIWL of 1800 kV, a gap of 4 meters will be sufficient. However, for, the SIWL of 1600 kV a gap of 8.6 meters will be necessary at the standard reference atmosphere. Over this gap of 8.6 meters, the LI withstand voltage will be as high as 4285 kV.

The air clearance evaluation is based on the voltage level of 50% breakdown probability, U_{50}. The required U_{50} is in turn calculated from the required withstand-voltage, U_w, i.e. SIWL, as below in equation (1). The values used for the standard deviation, σ, is 0.06 for Switching overvoltage and 0.04 for DC. The number of the standard deviations, n, to be used will depend on the accepted breakdown probability. In case the air clearance is designed for insulation, n=2 has been used. In case the air clearance is introduced to ensure personal safety, n=5 are recommended.

$$U_{50} = \frac{U_w}{(1 - n \cdot \sigma)} \quad (1)$$

The value of U_{50} shall be converted to the standard reference atmospheric conditions since most results from laboratory study have been presented at these conditions. For the valve hall, a maximum air temperature of 60°C and minimum relative humidity of 10% have been assumed.

For switching overvoltage, the air clearance, will be estimated based on the well know Paris formula for rod-plane gap (d in meters and U_{50} in kV).

$$d = \left(\frac{U_{50SI}}{500 \cdot k} \right)^{1/0.6} \quad (2)$$

The dielectric strength of a different air gap structure may be estimated from rod-plane gap through the introduction of the gap factor, k.

B. Study on the breakdown characteristics

To facilitate the insulation design of UHVDC systems, laboratory studies have been conducted on the multiple-gap system, representing the situation inside the converter valve hall. The electrodes used here are often of a large curvature. They are located at the places surrounded by grounded objects such as the walls of the valve hall. Many useful results have been obtained and applied in the valve hall design. Some of the intriguing observations are given in figures 4-6 [9].

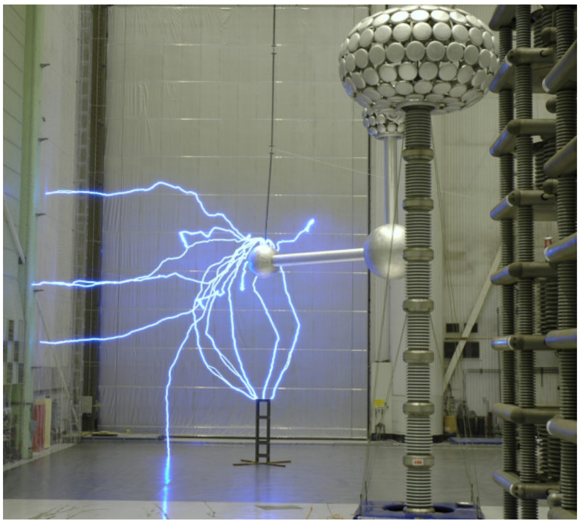

Fig. 4. Photograph of breakdown trajectories in a test set-up

It is well know that breakdown trajectories often not take the shortest way to bridge the gap. In an insulation arrangement with a high voltage electrode surrounded by several grounded objects, i.e. a multiple-gap system, the breakdown may take place over longer gap spacing instead of the shortest one. This is especially the case when several long gaps are stressed simultaneously by a switching impulse voltage.

Such phenomena have already been observed and studied in the 60's during the development of equipment for EHV transmission system. The breakdowns with trajectory bridging the longer gap instead of the shorter one, which is often the real test object, were referred initially as "anomalous" breakdown. But, it was soon realized as rather normal. Today, this phenomenon has been better understood thanks to the deeper knowledge on the streamer and leader mechanism, the vast study on the gap factors of various gaps structures, and increased capability on electric field simulation.

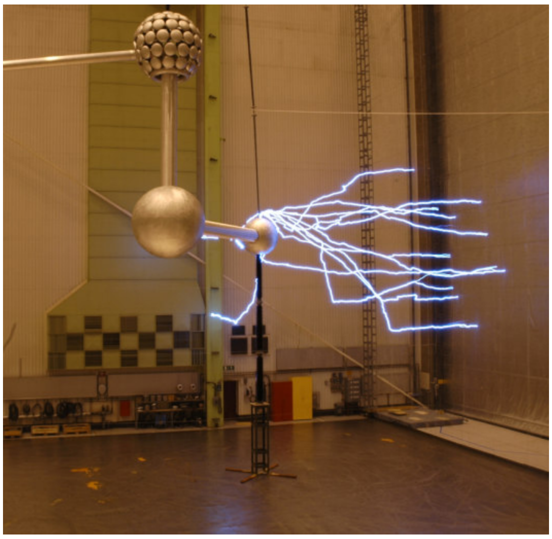

Fig. 5. Photograph of breakdown trajectories in a test set-up

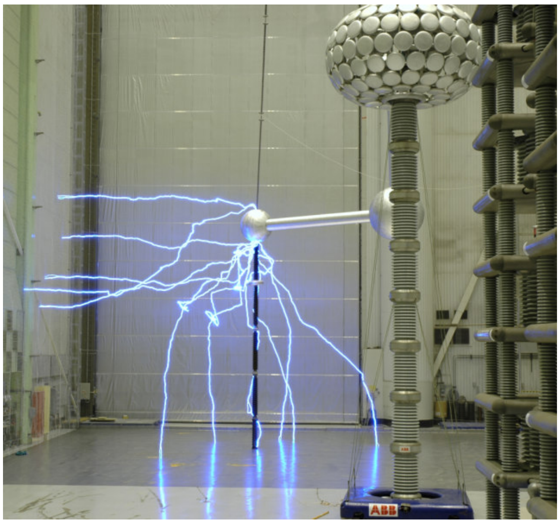

Fig. 6. Photograph of breakdown trajectories in a test set-up

C. Categories of gaps in valve hall

The equipment found in a DC valve hall normally comprises but is not limited to:

- Thyristor valves
- Arresters
- Bushings connecting to the DC yard
- Bushings connecting to the converter transformers
- Grounding switches

The above equipments are interconnected with bus-works. Based on the voltage stress and valve hall conditions, air clearances, shielding, and bus dimensions are designed.

The gaps in the valve hall have been divided into three categories:

1. gaps between the equipment structure and the surrounding objects at different potentials
2. gaps between the connecting bus-works and the surrounding objects at different potentials
3. safe distances to where the presence of personnel during operation is possible

For gaps between the equipment structures to the surrounding objects at different potentials, the required air clearances and shielding given by the equipment supplier have been fulfilled. It is important to realize that the insulation system of the high voltage equipment is designed with coordination between its internal insulation and external insulation. Any possible conflict or difference between valve hall clearances and the clearances required by the equipment supplier shall be presented to and agreed upon with the equipment supplier.

For gaps between the connecting bus-works to the surrounding objects at different potentials, the required air clearances have been determined based on the electrode form and gap configuration. The shielding and bus dimension have been determined by:

- corona free under maximum operational voltage
- dielectric strength under the required withstand voltage
- Current carrying ability
- Mechanical strength
- Other constraints

The configurations of terminations and connections of the bus-works to the equipment have been presented to and agreed upon with the equipment supplier.

In most of HVDC project, no presence of person inside the valve hall is allowed during operation. For the safe distances to where the presence of person during operation is possible, the greatest caution must be exercised. This is specially the case for UHV projects. The instability of the long arc from an air insulation breakdown of a long gap is well documented. Therefore, the design principle with 5×σ has been adopted.

Fig. 7. HV valve hall at Fengxian station, XS800 project of SGCC

V. Converter valves

A. Design conditions

In this project, double valve structure is used, see fig. 1. The pole voltage of 800 kV DC is shared by four double valve structures in series. Each single valve is protected by a valve arrestor. The over-voltages are "shared" by arrestors.

Fig. 8. A double valve for 3GC project at test position

To obtain an optimized layout of the converter station including valve hall, several single valves in the converter groups can be integrated mechanically into one structure and become a multiple-valve-units (MVU). The most common structure of MVU is a quadruple, i.e., four series single valves in one structure. Another often used structure, as that used in 3GC, 3GG, and 3GS projects, is the double valve structure. For most of the valves designed by ABB for classic HVDC project, the valve is in the form of continuous loops of thyristor modules. There is no special insulation between terminals of successive single valves.

The insulation design for MVU is to determine the air clearance from the MVU structure towards the surrounding objects at different potential and the shapes of shielding electrodes if needed. In most cases these surrounding objects are walls of valve hall at ground potential. The shapes of electrodes are determined by DC voltage to ensure a corona free operation. The air clearance is determined by the SI.

In this project, for double valves inside the HV and LV hall, all double valves in the same hall are installed with the same suspension and having the same distance to floor and walls. Therefore, the length of suspension and distance to floor and walls in the HV hall are determined by valves between 800 and 600 kV DC buses. In the LV hall these distances are determined by valves between 400 and 200 kV DC buses.

B. Principle of Dielectric tests on MVU

The dielectric tests of converter valves are conventionally divided into three categories: test on valve support structure, test on single valve, and test on MVU. For this project, the tests of the first two categories are similar to all other earlier projects. The tests on MVU are somewhat different because that there are four double valve structures between the pole and the neutral.

As stated in IEC60700-1 [10], the principal objectives of MVU dielectric tests are:

1. to verify the voltage withstand capability of the external insulation of the MVU with respect to its surroundings, especially for the valve connected at pole potential:
2. to verify the voltage withstand capability between

single valves in a MVU structure:

3. to verify that the partial discharge levels are within specified limits.

Objective 2 is not relevant in this case. The MVU of this project is a double valve. Internally, the most onerous condition (dimensioning condition) is when one of the two valves is in conduction. Furthermore, there is no special insulation structure between single valves in the MVU.

For objective 1, SI will be the dimensioning stress. For objective 3, DC will be the dimensioning stress. Since LI is not the dimensioning stress, and the design according to the dimensioning factor will results in higher margin for LI withstand, test under LI is not necessary.

C. Determination of the test object for MVU tests

In order to fulfill the objective 1 and 3 of the MVU tests, the main task is to set-up correctly the test object to make it possible to apply the voltages that specified for 800 kV DC and 400 kV DC poles on the test object. One alternative is to set-up several (more than one) double valves to share the whole voltage. Let us name this alternative as "multiple-double-valves" solution. The other alternative is to set-up only one double valve and use suitable capacitive or resistive components to share the voltage, referred here as "one-double-valve" solution. The "one-double-valve" solution has been used for the MVU test of 3GC projects.

Before making comparison between these two alternatives, it is important to understand that the voltage distribution between individual valves is not an issue that needs to be verified in MVU tests. The maximum voltage stress over each single valve is determined by the arrestor protection scheme. The multiple-double-valves solution can not provide a better simulation of real voltage distribution than one-double-valve solution. Contrary to such belief, since the valve test will be performed without the protection of arrestors and there will be differences between the layout in valve hall and in test laboratory, incorrect voltage distributions along the long valve-chain may occur in the multiple-double-valves. Such incorrect voltage distribution may generate a risk that a certain part of the valve in this long chain will be triggered resulting in overstress on other valves.

From test technique point of view, the only advantage of the multiple-double-valves solution is that most of the components needed to share the test voltages are installed in valve structures. Whether or not separate components will still be needed depend on how many double valves will be installed and also on how many valve modules will be mounted inside these double valves. The disadvantage of the multiple-double-valves solution is, as just mentioned above, unrealistic voltage distributions along the long valve-chain may occur.

Also from test technique point of view, the advantage of one-double-valve solution is that the risk related to the unrealistic voltage distribution along a long valve-chain can be avoided. The voltage across the tested double valve is under a better control. The trade-off is that several separate components will be required to share the test voltage. Most of these separate components are relatively easy to obtain. These are the capacitors to be used in SI test and the resistors to be used in DC test. However, for LI test, if it will be performed, without suitable reactors to share the voltage, a relative large numbers of valve reactors may be needed to be installed separately. This set-up requires additional insulation design and construction work. For this project only for LI test on the DC 800 kV pole level such arrangement may be required

From project engineering point of view, the advantage of one-double-valve solution over the multiple-double-valves solution is obvious. If three double valves are to be installed, everything will be almost three times, the used material, the space needed in the laboratory, the installation and dismounting time.

Fig. 9. A double valve for XS800 project at test position

Considering the fact that LI is not the dimensioning factor for the MVU, and that the test under LI will not produce any further confidence in the insulation design for the end user, it is technically well justified to remove the LI test form the test program for the MVU in the HV hall. The LI test will anyway be performed on the MVU in the LV hall. By removing LI test from the test program for the double valve in the HV hall at 800 kV DC pole voltage the only "disadvantage" of one-double-valve solution is eliminated.

D. Dielectric type test program

The dielectric type test program includes briefly the following tests:

- Tests on valve support structure for valve suspensions in both HV and LV halls
- Single valve tests
- MVU test for both valves in HV and LV halls with: DC and SI tests on a double valve structure in HV hall; DC, SI and LI tests on a double valve structure in LV hall

The valves for the XS800 project have passed all the dielectric test successfully.

VI. Summary

Through close cooperation between the supplier and the utility, many challenges in the external insulation design of XS800 project have been met with well grounded solutions. In this paper, the important issues in the external insulation design of DC yard, valve hall, and for converter valves are presented. It is the intention of this paper to review and summarize the work that has been done and the decisions that have been taken to the benefit of further work and design of new projects.

VII. Acknowledgment

The authors gratefully acknowledge the contributions of the XS800 project teams of ABB HVDC and SGCC.

VIII. References

[1] D. Wu, U. Åström, Z. Su, W. Ma, "Critical issues on the dimensioning of external insulation for UHVDC converter stations", *2006 International Conference of UHV Transmission Technology*, Beijing, China, 2006.11.

[2] D. Wu, Z. Su, "The correction factor between DC and AC pollution levels: review and proposal", *10th ISH*, Montreal, Canada, August 25-29, 1997.

[3] Z. Su, W. Ma, D. Wu, U. Åström, G. Karlsson, "Measurement of site pollution severity under DC voltage by means of a portable test station", *14th ISH*, Beijing, China, August 25-29, 2005.

[4] U. Åström, B. Almgren, D. Wu, "Outdoor insulation design for the Three Gorges-Changzhou ±500 kV HVDC Project", *Proceedings of International Conference on Power Systems*, Set. 3-5, 2001, Wuhan, China

[5] D. Wu, U. Åström, Z. Su, W. Ma, "The design and operational experience of an indoor DC-yard for ±500 kV HVDC transmission" *15th ISH*, Ljubljana, Slovenia, August 27-31. 2007.

[6] W.M. Ma, B. Luo, Z.Y. Su, Z.P. Dang, Z.C. Guan, X.D. Liang, U. Åström, D. Wu, E.Y. Long, H.G. Sun, "Preliminary recommendations on the suitable shed profile for HVDC station insulators with silicone rubber housing", *2006 International Conference on Power System Technology*, Paper DC1-07, C1538, Chongqing, China, 22-26 October, 2006.

[7] D. Wu, R. Hartings, U. Åström, B. Almgren, S. Nord, "The performance of station post insulators for UHVDC applications" 10th ISH, Montreal, Canada, August 25-29, 1997.

[8] B. Almgren, U. Åström, D. Wu, "Operational experiences of insulators in HVDC converter stations" *Proceedings of the eleventh national power systems conference*, NPSC-2000, Bangalore, India

[9] L. Ming, D. Wu, U. Åström, G. Asplund. "Intriguing observation on the breakdown trajectory of large air-gaps under switching impule voltages", *16th ISH*, Cape Town, South Africa, August 24-28. 2009.

[10] IEC 60700-1 "Thyristor valves for high voltage direct current (HVDC) power transmission – Part 1: electrical testing" First edition, 1998-09