Paper presented at INMR World Congress 2017, Barcelona-Sitges, Spain, 6-8 November, 2017

Innovations, Developments & Remaining Challenges for UHV Insulator Design

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ABSTRACT

For UHV applications, the main challenge on insulator design is to fulfil the required length and mitigate the negative effects on insulation and mechanical performance caused by the increased length. Efforts can be made on system design by reducing the levels of switching over-voltages. The required creepage distances could also be reduced through the use of insulators with hydrophobic surface. Indoor solution can provide the conditions to reduce the required arcing distance by the improvement of the electrode design. In this report, the impacts of system parameters on the insulator design have been reviewed. On the other hand, Insulators with different type of materials and production techniques have been developed and are available. These include the porcelain insulators with hydrophobic coatings, hybrid insulator, and composite hollow-core insulators with different solution for internal insulation. It is important to know the strength and weakness of these insulators in order to make a correct selection. In this report the design issues and solutions related to external and internal insulation design of insulators for UHV applications have also been reviewed with emphasis on the post insulators made of composite hollow-cores.

KEYWORDS

External insulation; UHV; UHVDC; Insulators; Station Post Insulators; Composite Hollow-core Insulators.

INTRODUCTION

Insulators are components of power systems. The design of insulators should accommodate the system requirement. System requirement includes the voltage and current levels, the ambient conditions, the layout, and mechanical strength. The combinations of these parameters result in large variety in applications. Efforts have been made by the industry to standardize the design of insulators. However, to enable an optimized system design it is necessary to make adjustment in the design or to make a new design. This is especially the case for systems with unconventional requirement, such as the Ultra High Voltage (UHV) system. In an earlier presentation [1] the design principles for external insulation at UHVDC converter stations have been reviewed. In this report, more specific discussions will be given on the design of insulators for UHV applications.

UHV SYSTEM REQUIRMENT ON INSULATORS

Voltage levels

Some typical voltage levels for UHV are listed in table 1 below. For AC system the voltage levels are found in IEC standard [2]. For DC system the voltage levels are those often found in project technical specifications. For easy comparison, both peak and effective (r.m.s.) levels are given for AC voltage.

Table 1, examples of voltage levels specified for UHV systems

	AC system		DC system
800 kV	r.m.s.	peak	
System voltage, kV	800	1131	± 800
Phase/pole to earth voltage, kV	462	653	800
Switching withstand voltage (phase/pole to earth), kV		1550	1600
Lightning withstand voltage (phase/pole to earth), kV		2100	1800/1900
1100 kV			
System voltage, kV	1100	1556	± 1100
Phase/pole to earth voltage, kV	635	898	1100
Switching withstand voltage (phase/pole to earth), kV		1800	2100
Lightning withstand voltage (phase/pole to earth), kV		2550	2400
1200 kV			
System voltage, kV	1200	1697	
Phase/pole to earth voltage, kV	693	980	
Switching withstand voltage (phase/pole to earth), kV		1950	
Lightning withstand voltage (phase/pole to earth), kV		2700	

For insulators, the dimensioning parameter is, in most of cases, one of the following two:

- Creepage distance determined by the pollution performance under the effective level of phase/pole to earth operation voltage.
- Arcing distance determined by the SIWV (switching impulse withstand voltage).

For corona free design of terminations, the peak operation voltage should be used. In a few cases LI (lightning impulse) may become dimensioning for internal insulation of some apparatus. As listed in Table 1, for dimensioning parameters, UHVDC systems will face more stringent task than UHVAC systems. Most of the discussions given in this report have been based on the design of UHVDC systems.

Dimensioning parameters

Insulator lengths determined by either creepage distances or by arcing distances may be compared in figure 1 [3]. In this figure, the relationships between operation voltages and insulator lengths deducted from creepage requirement are plotted in red dash-lines. For three required USCD (unified specific creepage distance) values: 35, 43, and 54 mm/kV, the required insulator lengths have been calculated for DC pole to ground voltage of 500, 800, and 1100 kV, with a CF (creepage factor) value of 3.2. As an example one can find that:

43×800/3.2=10.8m.

The relationships between SI voltages and insulator lengths are plotted in blue lines. Here the rod-plane relationship is used and based on the formula:

$$U_{50} = 1080 ln(0.46L + 1)$$

The levels of SIWV required by 500, 800, and 1100 kV DC systems have been converted into 50% breakdown voltage, U_{50}, with two sigma's of 6%. The corresponding U_{50} levels have been rounded up to 1300, 1800 and 2390 kV. The corresponding insulator lengths (arcing distances) can therefore be estimated, as marked in blue dash-arrows.

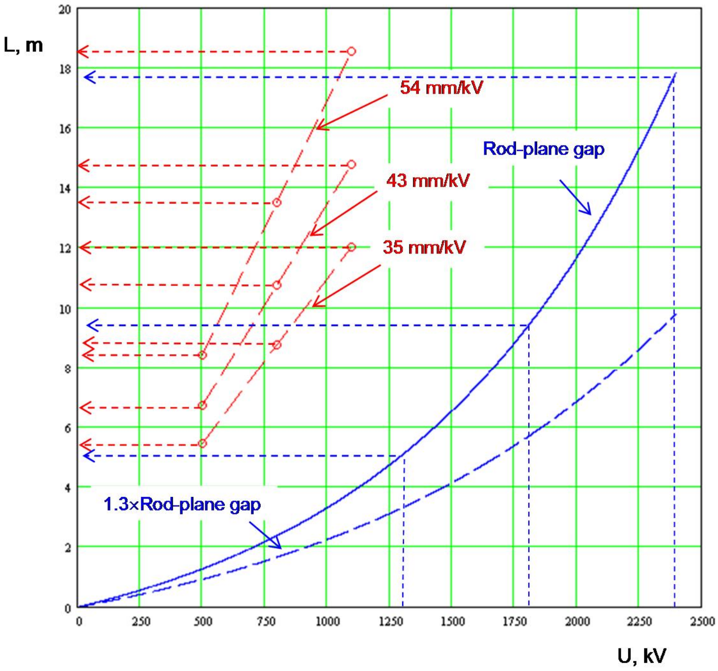

Figure 1. Insulator lengths determined by USCD for DC voltages of 500, 800 and 1100 kV (curves in red dash-lines); or by the U_{50} of SI of 1300, 1800 and 2390 kV respectively (curves in blue lines).

There are many parameters that may alter the values given in figure 1. For insulator lengths obtained through creepage, the final values will be influenced by the insulator surface materials, CF values, and diameters. A more decisive parameter will be the level of SPS (site pollution severity). For lengths obtained through arcing distances, it will be influenced by the gap factor resulted by the installation structures. Nevertheless for UHV applications the insulator length will be in most cases longer than 10 meters.

Indoor or outdoor DC yard

To mitigate the difficulties in the design of insulators for UHVDC application, there have been intensive discussions on whether or not the DC yard should be built indoor. Not much of such discussions has been reported for UHVAC applications. This could partly due to the readiness of gas insulated substations for AC applications. The other reason is the well know pollution problems under DC voltage. Under UHVDC, these parameters: insulator length, mechanical strength, insulator diameter, and pollution performance, could form a run-away loop. Therefore to build an indoor DC yard becomes an attractive alternative.

Another situation needs to be considered is the saturated relationship between arcing distance and the switching impulse when it comes to the UHV levels. For 1100 kV UHVDC, the arcing distance of an insulator may need to be as long as some 18 meters in order to ensure an U_{50} of 2390 kV under switching impulse. At the same time, the required length by creepage may be shorter than 18 meters. SIWV may become the dimensioning parameter. For indoor conditions, the arcing distance can be reduced by creating a larger gap factor than that of a rod-plane gap, through the improved structure of the electrodes. For outdoor conditions, however, pollution and rain will eliminate the screen effects of large electrodes. Higher gap factors than that of a rod-plane gap may become difficult to achieve.

For indoor DC yard, there is no need for a stringent humidity control. Without natural precipitation, the wetting of pollution by condensation and absorption is a relative slow and mild process. The stress on insulator is less severe than under natural precipitation. Even if, in the very unlikely situation, the pollution level inside an indoor DC yard may have reached the so called "very heavy" level [4], a study has shown that a porcelain insulator with an USCD in the range of 30 to 40 mm/kV can withstand such extreme severity [5]. Without needing the humidity control, the indoor design becomes economically more attractive.

INSULATOR DESIGN FOR UHV

External insulation of the insulator

For outdoor applications, characteristics of the surface materials, the shed profiles, the diameters, and the required USCD's in relation to SPS have been discussed in depth in literatures including several CIGRÉ and IEC technical guidelines, e.g., [4] [6]. For UHV applications at outdoor conditions, the challenges come mainly from how to mitigate the negative effects of the long insulator with large diameters in bad weather like fog, rain and snow. This is specially the cases for insulators installed vertically or with a small angles from vertical. Under UHV, it becomes difficult to simulate in laboratory the effects of water accumulation, distribution and cascading along an insulator of more than 10 meters in length. There is not yet enough data that could give exact account of those effects on the breakdown voltages [7]. In some cases, insulators of multiple-columns have been used which also lead to design uncertainties. Other factors that could further complicate the situations are the effects of the metallic flanges, the height and shape of the steel pedestals. Such a complicated situation could somehow be realized by observing the photo of an 800 kV UHVDC outdoor DC yard in figure 2. In this DC yard, all insulators under 800 kV DC pole voltage are of some 11 meters in length. It could also be envisaged from this photo on what challenges would be encountered if an 1100 kV UHVDC DC yards with insulators of length of some 18 meters will be build.

Figure 2. An outdoor DC yard of XS800 project of SGCC

For UHV applications, it has become a production technique issue to manufacture porcelain post insulators with large core diameters. Post insulators made of composite materials have emerged as alternatives to porcelain insulators. One of the attractions is the use of HTM (hydrophobicity transfer material) surface with improved external insulation strength. The downside is the emergence of internal insulation issues. A comparison made more than 10 years ago [8] lead to the decision that all the post insulators in the DC yard in figure 2 were made of porcelain and covered with RTV. By relying on the hydrophobic property of the coating, the required USCD has been reduced by 20%. The insulators that otherwise would be of some 14 meters in length became 11 meters instead. As a result, the core diameter was also slightly reduced resulting in reduced quality risk in manufacture processes. It is worth to mention that the two smoothing reactors in figure 2 weights more than 60 tons each. The consequence of mechanical failure overwhelms consequence of eventually external insulation flashover.

Internal insulation of the insulator

For apparatus, like bushings, the internal insulation design is another technical area and not included in this report. However, the internal insulation design has certain impact on external insulation through electric field grading. For vertically installed apparatus with internal axial voltage grading, the interactions between the internal voltage distribution and external voltage distribution need special attention. The differences between internal and external voltage distribution may lead to failure/puncture of the hollow-core insulators.

For cap-and-pin line insulators and porcelain post insulators, there has been little internal insulation issues. Failure of glass or porcelain insulators were due to issues related to material quality. However, for long-rod composite insulators there are internal insulation issues. It is well know that the moisture ingress along the material interface and inside the rod may cause insulation problem and lead to failure.

Shown in figure 3 is a post insulators of composite hollow-core. The main challenges for this type of insulators are to determine the suitable materials used for internal insulation and the methods used to prevent leakage and/or moisture ingress. The potential leakage paths are marked figure 4.

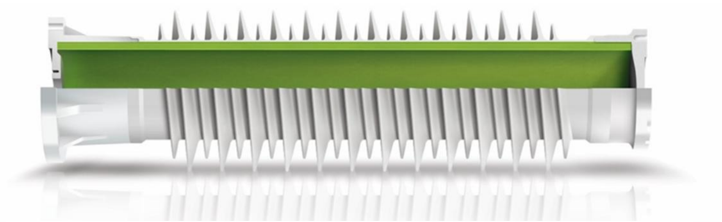

Figure 3. A composite hollow-core post insulator

Several materials have been used as internal insulation:

1. Solid epoxy rod,
2. Polyurethane (PUR) foam,
3. PVC foam,
4. Pressurized gas,
5. Low pressure (near atmosphere) gas.

There is also the hybrid type of post insulators with porcelain core and silicone rubber sheds available on market. In general, the weakest point of internal insulation is at the interfaces. For internal insulation with materials 1-3 listed above, a relative rigid interface will be introduced between the core and the tube of the hollow-core insulator. This interface may suffer from the risk of moisture ingress already in manufacturing process. There are also risks in the operational conditions. During operation, when subjected to mechanical stresses, the peel stress will increase at the interface. Foams are better off at such conditions than solid rod, since foam is softer and follows better with the movement of the tube. There is no available method to monitor such risk after assembly.

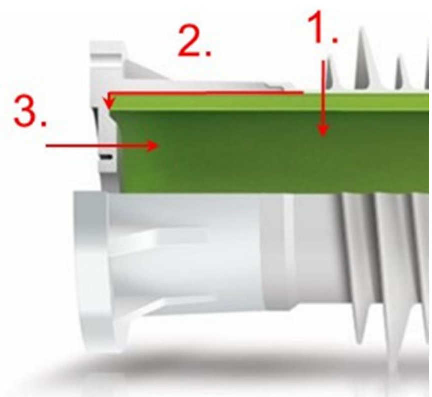

Figure 4. Potential leakage paths marked in red. Path 2 & 3 are of higher risk.

Insulator filled with pressurized gas is not a new technique. For apparatus with hollow-core insulators, in order to increase the strength of internal insulation, pressurized gases have been widely used at all voltage levels for various types of apparatus. Figure 4 is an UHVDC 1100 kV wall bushing insulated with pressurized gas. For such applications, gas leakage will resulting in the reduction of the strength of internal insulation. Therefore, gas pressure needs to be monitored. A small gas bushing has been installed and used to fill up the gas during maintenance if it is necessary. However, such a gas bushing itself may become a weak point for leakage.

Figure 5. An UHVDC 1100 kV wall bushing

For station post insulators filled with gas, it is not necessary to have pressurized gas. The arcing distance inside and outside is of the similar length. While the external insulation will be stressed by various ambient conditions, the internal insulation is under a well-controlled condition. Therefore to have gas pressure close to that of ambient will be sufficient for the purpose of insulation. With a smaller pressure difference between the inside and outside of the insulator, the risk of leakage will be reduced. Furthermore, the potential leakage paths, 2 and 3 as marked in figure 4, should be secured by redundant sealing solutions and accurate tightness testing. Since the strength of internal insulation does not rely on a higher gas pressure, there is no need to monitor and refill. No gas bushing is needed which will eliminate this weak point.

CONCLUSIONS

For UHV applications, the main challenge on insulator design is to fulfil the required length and mitigate the negative effects on insulation and mechanical performance caused by the increased length. Efforts can be made on system design by reducing SIWV levels. The required USCD could also be reduced through the use of insulators with HTM surface. Indoor solution can provide the conditions to reduce the required arcing distance by the improvement of the electrode design. On the other hand, Insulators with different type of materials and production techniques have been developed and are available. It is important to know the strength and weakness of these insulators in order to make a correct selection.

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