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Selection between indoor or outdoor DC yards

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SUMMARY

In an HVDC converter station, the area where the DC apparatus are installed is referred to as the DC yard. Most common until now, apparatus in the DC yard are installed directly outdoor. However, in some cases, a closed shelter (a hall) is erected with DC apparatus installed inside. This is an indoor DC yard. To select between the indoor or outdoor solutions for a DC yard, there are many factors that will need to be weighted in.

- With the outdoor solution and with the DC pole voltage up to 600 kV, the operational experiences in the last two decades have been satisfactory, mainly thanks to the application of hydrophobic coatings and silicone rubber insulators.
- The uneven-wetting problem on horizontally installed wall bushings has been solved successfully through the application of hydrophobic coatings and silicone rubber insulators.
- Station post insulators of porcelain with and without hydrophobic coatings have been used for outdoor with satisfactory performance with pole voltage up to 600 kV. Station post insulators with silicone rubber sheds are available today.
- With the pole voltage of 800 kV and in polluted areas, to fulfill the mechanical requirement, it is necessary to use shorter creepage distances on silicone rubber insulators and porcelain insulator with hydrophobic coatings than that on porcelain insulators if the outdoor solution is preferred.
- For the future pole voltage of 1100 kV, increased difficulties will be encountered in realizing an outdoor solution. Indoor solution may be more attractive.
- An indoor solution will to a great extent release the difficulties for coordinating the internal and external insulation for vertically installed apparatus especially for UHVDC applications.
- Although pollutants will appear inside the DC yard building, the frequency and intensity of wetting are significantly reduced in comparison to outdoor. If the level of relative humidity is under control, wetting of pollution can be eliminated. With the short creepage distances needed, a significantly compacted design can be achieved.
- The major cost of the indoor solution is the building. This cost can partly be compensated by the reduced cost of apparatus. An improved reliability is the most important aspect in choosing the indoor solution.

KEYWORDS

HVDC Transmission system, UHVDC, External Insulation, Insulators, Converter Station, DC yard.

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1. INTRODUCTION

In an HVDC converter station, the area where the DC apparatus are installed is referred as DC yard. Most common until now, apparatus in the DC yard are installed directly outdoor. However, in some cases, a closed shelter (a hall) is erected with DC apparatus installed inside. This is an indoor DC yard.

With the DC system voltage up-to 600 kV, the operational experiences of converter stations with outdoor DC yards have generally been satisfactory, especially in the last two decades. The number of flashovers caused by pollution has been significantly reduced by the application of hydrophobic coatings on porcelain insulators and by the application of silicone rubber insulators [1]. In a few cases where indoor solution was adopted because of the extreme and increasing pollution levels, the operation experiences have been highly satisfactory and the indoor solution is welcomed by the operational personal [2].

For UHVDC system with 800 kV, difficulties had been encountered in the design of outdoor insulators. It was difficult to fulfill both the insulation and the mechanical requirements. Such a risk was identified and also the solution [3]. Today, both outdoor and indoor solutions have been adopted in different 800 kV UHVDC projects. The other reason for selecting the indoor solution is to obtain a more compact design in order to reduce the land area occupied by a converter station. For apparatus within this weather protected building, the creepage distances needed and the mechanical strength required can be reduced [2]. Switching impulse voltage may become the dimensioning parameters. Electrodes with larger diameters can be adopted to reduce the required air clearances.

In this paper, the technical aspects related to the selection between indoor and outdoor solutions are presented based on operational experiences and design requirements. The requirements for indoor ambient conditions and indoor insulation design are discussed. Such discussion is applicable even for future UHVDC system with a pole voltage higher than 800 kV.

2. OUTDOOR DC YARD

2.1 General

In the DC yard, insulators used are mainly two types, hollow-core insulators as housing for apparatus and post insulators for supporting the bus-bar and apparatus. Until early 1990s, most of those insulators used were porcelain insulators. Problems with flashovers caused by rain and pollution were severe in 80s on porcelain insulators [1]. Various mitigation measures were introduced. The applications of different types of hydrophobic coatings on porcelain insulators have been proven to be the most successful alternative. Since early 1990’s, apparatus with composite hollow-core, i.e., with glass-fibre reinforced epoxy-resin tube and silicone-rubber sheds, appeared in the DC yard. 10 years later, in 2000’s, all apparatus in DC yards can be delivered with composite hollow-core insulators. Operational statistics until year 2000 showed that by counting the number of flashovers per pole per year among more than 70 operating poles, an excellent record of 0.04 had been achieved since 1995 [1]. This trend has been kept until now with only few flashovers reported from the stations in the last two decades.

2.2 Wall bushings

In a converter station wall bushings are used to connect the converter valves located inside the valve hall to the outdoor apparatus. The wall bushings connected to the pole voltage is subjected to the highest stress. In most cases, wall bushings are installed at a near horizontal position on the side wall of the valve hall. At this position, the pollution level on wall bushings will be lower than other apparatus in the same station. It is well documented that insulators with larger diameters will catch less pollution than smaller insulators [4]. What is more important is that, at the horizontal position, insulators enjoy effective natural cleaning by rain [5]. Therefore, measured pollution levels on wall bushings were very low [6]. However, in this position, partial wetting of the bushing surface in rain may occur caused by wind and the shielding effect of the valve hall [6]. This phenomenon is referred to in literature as “uneven-wetting” or “uneven-rain”.

For porcelain bushings, uneven wetting was a severe problem in 1980s. A large number of flashovers had occurred on wall bushings due to uneven wetting [1]. Before the cause of those flashovers was identified, this problem was considered and handled as pollution flashovers. Very long creepage distances, e.g. up to 60 mm/kV, have been introduced on wall bushings with limited effect. The value of 60 mm/kV reached the production limitation of that time for 500 kV porcelain bushings in the horizontal position. Designs with the wall bushing vertically installed on the roof of the valve hall were also introduced with little success. A vertical bushing will suffer from both heavy rain and pollution flashovers [1].

Through intense studies worldwide by pollution measurements at different sites, correlation of the whether pattern with flashover statistics, and laboratory simulations, the mechanism of the flashovers caused by uneven wetting was revealed [6, 7]. Among many mitigation methods, including the installation of rain scattering net above the wall bushings, the most effective solution was identified, i.e. to keep the bushing surface hydrophobic. For porcelain insulators, this was achieved by the application of RTV or silicone grease coatings. For wall bushings with silicone rubber sheds, no flashovers caused by either pollution or rain have been reported since the application in early 1990’s. The range of creepage distances used on a bushing with silicone rubber housing has been between 23 to 45 mm/kV.

2.3 Station post insulators

Although presented in this section for station post insulators, most of the discussions regarding to the dimensioning of the insulators are applicable also to other apparatus in the DC yard.

For station post insulators, insulators with silicone rubber housing have only in recent years become available. At present, station posts made of porcelain are in the majority. With the DC pole voltage up to 600 kV, the performance of the station post insulators has been fairly satisfactory. For porcelain insulators, creepage distances between 35 and 54 mm/kV have been used in different stations. In many stations hydrophobic coatings have also been applied on these insulators. Among those cases where coatings have been applied, only in one case the application was aimed to mitigating pollution flashover on post insulators [1]. In all other cases, the applications of hydrophobic coating on post insulators were only adopted as precautions since flashovers occurred on other type of insulators in the same station.

For DC pole voltage of 800 kV, another parameter, the mechanical strength of the solid-core porcelain insulator, has become a critical dimensioning parameter. This may be illustrated by a simple calculation below.

1) With a given insulator shed profile, the relationship between the length of creepage and the dielectric strength is linear under moderate or heavy pollutions [4]. Therefore, if a creepage requirement of 54 mm/kV is specified for insulators with average diameters not more than 300 mm, the total required creepage for 800 kV will be 43200 mm.
2) The ratio between the creepage distance and the arcing distance is defined by IEC60815-1 [8] as the creepage factor (CF). For HVDC applications, the common range of CF for porcelain insulators is between of 3.2 to 3.7. However, when counting in the flanges, CF=3.2 is a more relevant value. Dividing 43200 by 3.2, the height of the insulator is will be 13500 mm.
3) To withstand the wind load and seismic requirement, the required core diameter for this insulator will be more than 300 mm. A solid-core insulator with such a core diameter is difficult to produce.
4) Furthermore, with a core diameter of 300 mm, the average diameter of this insulator will be larger than 300 mm which is the base for the creepage requirement. The required creepage, 54 mm/kV as given in step 1, needs to be increased. However, to increase the creepage requirement will lead to a further increase in the height of the insulator, as given in step 2.

5) Consequently, with the increase in height, a further increase in the core diameter may become necessary. Following the steps from 1 to 4 in a loop, a run-away situation may occur resulting in an unreliable design.

Alternatives for avoiding such a run-away situation have been studied [3, 9]. Without having to build an indoor DC yard, to use insulators with hydrophobic surface is the most realistic solution. For post insulators with silicone rubber sheds, there are three types available today:

- hollow-core silicone rubber insulators filled with insulating gas,
- hollow-core silicone rubber insulators filled with foam, and
- hybrid insulators, i.e., solid core porcelain with a silicone rubber housing.

All these three types have their merits and drawbacks. Technically, the hybrid type may be the most stable solution, while the gas-filled technique is more mature. Economically, the gas-filled could be the cheapest alternative. Both the gas-filled and the hybrid types have been adopted in different 800 kV projects.

For the Xiangjiaba-Shanghai ±800 kV UHVDC project, the first 6400 MW project, when the project planning started in 2004, all the above types of post insulators with silicone rubber sheds were still in the form of prototypes. Considering the reliability aspect and the tight time plan for delivery, a prudent approach has been taken by not introducing those prototypes into this project. It was determined that porcelain insulators with RTV coating will be used with a total height of 11 meters for 800 kV pole level. The resulting creepage distance was about 85% of that specified for porcelain insulators without coating. It was fully realized that the functional lifetime of RTV coating will be limited depending on the site conditions. Maintenance or even recoating may become necessary. After more than three years of problem free operation, in 2013, utility engineers had decided to recoat some of the insulators in one station based on a measurement on wettability class [10]. With the wettability class at level 6 in one measurement, recoating was a prudent action.

Conventionally, in the DC yard, the lengths of porcelain insulators are dimensioned by either the creepage requirement for pollution performance or the arcing distance requirement for switching-impulse (SI) withstand. As shown in figure 1, for different creepage requirements, e.g. 35, 43 or 54 mm/kV; and for different DC pole voltages, e.g. 500, 800 or 1100 kV, the lengths of the insulator, L, can be calculated and given in the red curves. With the probable U_{50} levels, 1300, 1800, or 2390 kV, for SI for the respective DC pole voltages, the required arcing distances, L, of the insulators can be calculated by, e.g. the rod-plane formula [11]:

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

As indicated in figure 1, for the DC voltage of 500 kV, the three creepage levels result in the lengths of porcelain insulators in the range of 5.5 to 8.5 meters. At the same time, the corresponding SI, 1300 kV in U_{50}, requires only 5

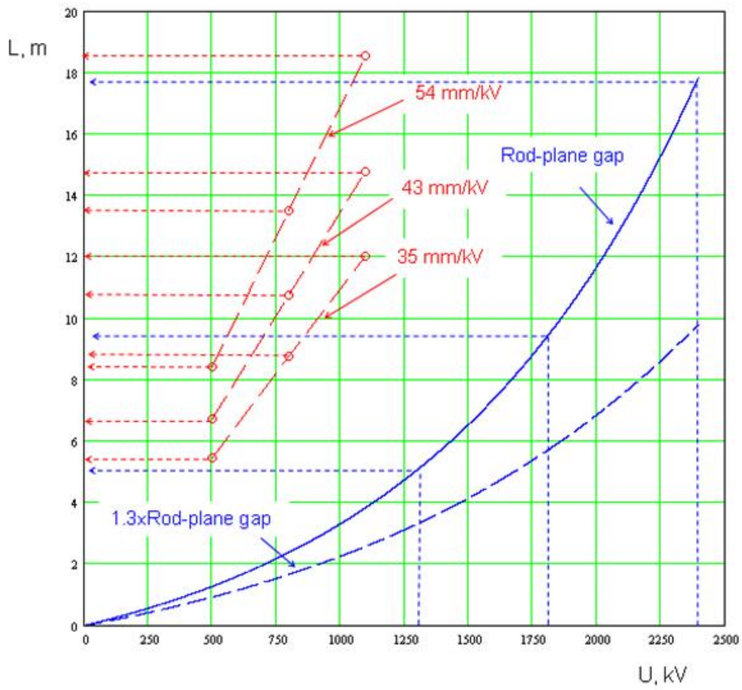

Figure 1. Insulator length determined by the required specific creepage distances, for DC pole voltages of 500, 800 and 1100 kV (curves in red color); or, by the required arcing distances for U_{50} of switching impulse of 1300, 1800, 2390 kV respectively (curves in blue color). For rod-plane gap [11]:

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

meters in arcing distance if rod-plane gap formula is used. However, for the DC voltage of 1100 kV, the switching-impulse voltage may become the parameter that determines the insulator length. Even if much shorter creepage distances will be accepted for insulators with hydrophobic surface such as silicone rubber insulators, the total length of the insulator will still be in the range of 15 meters or more. In such cases, the criteria for the design will be changed, since there is little one can do to improve the SI withstand level in rain at outdoor conditions. With this height, the mechanical reliability and the rigidity of post insulators in high wind will become difficult issues to handle.

2.4 Other apparatus insulators

Since most of the apparatus in DC yard have either been coated with hydrophobic coatings or equipped with silicone rubber housing, the number of flashovers reported has been much lower than the time when only porcelain insulators were used [1]. For apparatus with silicone rubber housings, the creepage distances used have been, in most of the cases, shorter than that of porcelain insulators. The typical value is in the range of 75 to 80% of that of porcelain insulators. Even with rather large diameters, 400-600 mm, the creepage distances are equal or below 45 mm/kV in most of cases.

For the cases that certain incidents did occur on apparatus with coated porcelain insulators or with silicone rubber insulators, the results were often insulation breakdown and damaging of the apparatus. These incidents may be attributed to the problems in the internal-insulation design as well as the improper coordination between internal and external insulation. Typical situations could be that:

- a significant difference in voltage distribution between internal and external insulations,
- lack of internal DC grading,
- weak spots at internal insulation where high electric field appears at sharp metallic parts,
- insufficient insulation strength at radius insulation in the internal insulation design.

Noticeably, all those incidents were occurred on vertically (or near vertically) installed insulators. During wet conditions, especially in rain, partial discharges appeared at the external surface of those insulators. These discharges may lead to internal discharges and the reduction of the surface hydrophobicity of the external insulation. For porcelain insulators with coatings, the insulators were often ruptured together with the flashovers. For insulators with silicone hollow-cores, traces of discharge were often found at the inner surface of the hollow-core insulators. For vertical apparatus, the coordination between internal and external insulations has been a challenge in the design. This is especially the case with higher pole voltages.

3. INDOOR DC YARD

3.1 Ambient conditions

The building of an indoor DC yard creates significantly different ambient conditions compared to outdoor. Furthermore, this is a predictable and stable condition. The main differences in ambient conditions are briefly summarized in table 1.

Table 1, Differences in ambient conditions between outdoor and indoor DC yards

	Outdoor	Indoor
Pollution	Site dependent. Both dry and wet pollutants, e.g. in form of salt fog may appear. The accumulation rate is determined by the site conditions.	Less pollution may be accumulated depends on the tightness of the building. Static electric field is the main force that attracting dust to the DC equipment. Only dry pollution will appear. The accumulation rate is lower than outdoor.
Rain	Rain will wet and also wash away the pollution. Rain may lead to shed bridging and flashover on vertical insulators.	No rain.

Fog	Fog will wet pollution and may cause pollution flashover.	Fog will not be able get into the building as long as it is enclosed.
Humidity	High humidity will wet the pollution and may lead to flashovers.	High humidity will wet the pollution and may lead to flashover.
Temperature	Condensation may occur due to the temperature differences between the insulator surface and ambient.	A possible higher indoor temperature, due to equipment losses, than outdoor will reduce the relative humidity indoor and reduce the risk of condensation.
Wind	Wind load can be a dimensioning parameters for long insulators.	No wind.
Snow, ice	May cause flashovers.	No snow and ice.
Earthquakes	Seismic requirement can be a dimensioning parameter for high apparatus.	Same seismic requirement as outdoor but apparatus are lower.

3.2 External insulation in indoor DC yard

Building indoor DC yard cannot totally prevent the pollution accumulation on insulators. It will, however, reduce the amount of pollutants and the rate of pollution accumulation. Although in some cases, quick pollution build-up had been reported in indoor DC yard directly after energizing, this is probably due to the remaining dust from the installation activities. With time, years of operation, more pollution will be accumulated since there are no natural cleaning processes. However, dry pollutants, as long as they are not directly conductive, will not cause pollution flashover even with a large amount.

Inside the DC yard building, pollutants may become wetted by condensation or hygroscopic absorption. Condensation on the insulator surface may occur if the temperature of a porcelain insulator is lower than the dew point of the ambient air. The temperature of a porcelain insulator might become lower than the ambient air due to the thermal lag of the insulator. Study has shown, when assuming the temperature of the insulator is $2^{o}C$ lower than the ambient air (a difference of more than $2^{o}C$ is very unlikely) condensation may occur only when the relative humidity (RH) of the ambient air is higher than 80% [12]. As for the hygroscopic absorption, study on this subject has shown that this effect took place only when RH is higher than 75% [4]. For silicone rubber insulators, the effect of thermal lag is ignorable. On the surface of the insulator with materials that can transferring the hydrophobic property to the pollution layer, only pollutants that have not been engulfed by the silicone oil could be wetted by moisture absorption.

Based on such understanding, the pollution severity of an indoor DC yard should be categorized by the humidity level. If the indoor DC yard is built with a humidity control system, i.e., to keep the RH level less than 70%, the likelihood that the pollutants become wetted by condensation or moisture absorption is minimized. At such conditions, porcelain insulators with creepage distances in the range of 20-30 mm/kV can and have been used with good operational experience [2]. For indoor DC yard without humidity control system, condensation or moisture absorption may occur. However, since the level of wetting (the amount of water involved) is much lower than that in fog or rain, porcelain insulators with creepage distances in the range of 40 mm/kV can and have also been used with good operational experience. For silicone rubber insulators, a level of 30 mm/kV will be sufficient for applications without a humidity control.

The shed profile of an insulator is an importance issue for outdoor application. A suitable shed profile will collect less pollution, facilitate natural cleaning and, at the same time, have a higher dielectric strength in rain and fog. Such a suitable profile, especially in DC application, will result in a lower creepage factor, i.e. with relative large shed spacings. However, for indoor application, since the absence of the water dripping between sheds, insulator with a higher creepage factor can be adopted. This will lead to a further reduction of insulator length.

Under the indoor condition, the frequency and intensity of wetting events are significantly lower than that of outdoor. The level of surface leakage current and the risk of the development of partial discharges are also low. Therefore, the surface materials of insulators suffer less from aging than outdoor application. It should be sufficient to qualify the insulation surfaces with less severe tests, i.e. the Comparable Tracking Index (CTI) [13], instead of the stringent test for outdoor application as tracking and erosion tests [14]. In other words, if a silicone rubber insulator of outdoor type will be used, with little risk of tracking, the creepage distance can be further reduced from that of porcelain.

As discussed in section 2.3, the length of the insulator is also controlled by the requirement on arcing distance to withstand switching impulse. For outdoor conditions, the use of large electrode will not provide the needed improvement because of the water from rain [15]. For indoor conditions, the SI withstand under positive polarity can be improved by increase the size of the high-voltage electrodes. Therefore, the required arcing distance can be much shorter than that required for a rod-plane gap configuration. A real compact design will be achieved within a humidity controlled indoor DC yard with optimized air gap design.

The other benefit of the indoor condition, with reduced length of external insulation, is to make it easier to coordinate the internal and external insulation. Some of the incidents with apparatus failures initiated by rain as discussed in section 2.4 will be avoid.

3.3 The cost of indoor DC yard

The major cost of the indoor DC yard is the building, especially for UHVDC system. Wall bushings between valve hall and indoor DC yard need to be added. Certain auxiliary systems for a slow air circulation may be required with or without a humidity control. On the other hand, the cost of the building is compensated to a certain extent with the reduced costs of apparatus. Since there is no wind, the mechanical load on post insulators becomes much lower. The seismic requirement will become easier to fulfill on the indoor apparatus with a lower height. Furthermore, the costs of forced outages caused by the failure of insulation should be the critical factor in the cost evaluation.

4. SELECTION BETWEEN ALTERNATIVES

As an alternative solution to the pollution problem, the merits of an indoor solution are related to the type of pollution, the pollution severity, and the voltage level of the DC pole. Generally speaking, there are two types of pollutants, “type A” and “type B” [8]. The “type A” is characterized by dry pollutants, accumulating with time, and occasionally wetted (or cleaned) by precipitation. The “type B” is characterized by wet pollutants in the form of, e.g. salt-fog, and building-up rather quickly. This is the typical type of pollution near the coastline. There are also areas with combined pollution types.

For the areas with “type A” pollution, since the pollution will accumulate with time, there is time for a silicone rubber insulator to transfer its hydrophobic property to the pollution layer. In such areas, to use silicone rubber insulators provides the most optimized solution. This is especially true when the pole voltage is in the level of 600 kV or below. Only in one case, at a pole voltage of 500 kV, an indoor DC yard was built in such an area. The pollution was exceptionally high and expected to increase with time. Therefore a creepage requirement of 75 mm/kV was specified for station post insulators of porcelain [2]. The year was 1998 when the decision for adopting indoor solution was made. For the pole voltage in the level of 800 kV, the mechanical requirement of the insulator becomes a dimensioning parameter. The balance between the indoor and outdoor solution will probably be dictated by the pollution severity and corresponding creepage requirement. To be more precise, it is the creepage requirement for silicone rubber insulators that will dictate the balance. For a voltage of 1100 kV, the indoor solution becomes more attractive.

For the areas with “type B” pollution, there is certain degree of reluctance to use shorter creepage distances for silicone rubber insulators than that for porcelain insulators. The reasons are the concerning on the ability of hydrophocity recovery and on the effects of possible aging of the silicone rubber insulators. It should be realized, however, severe “type B” pollution in the form of direct sea-spray and dense saline fog affects only limited area, a few hundred meters or a few kilometers from the sea. The size of the area affected is related to the topography of the coastal area and the dominating wind direction [8]. Outside this area, the pollution will be more like “type A” in the form of dry salts. Therefore, indoor solution is not the only solution for all coastal environments. Nevertheless, for the areas that do suffer from severe marine pollution, indoor DC yards have been adopted more often than in “type A” areas even for pole voltage below 600 kV.

A matrix for the preferable solutions is proposed in table 2 based on operational experiences and available information today:

Table 2, the preferable solutions with respect to voltage levels, pollution types, and pollution severities

<table>
<tr><th rowspan="2">Pollution types</th><th rowspan="2">Pollution severities</th><th colspan="3">DC pole voltages</th></tr>
<tr><th>Up to 600 kV</th><th>800 kV</th><th>1100 kV</th></tr>
<tr><td rowspan="2">“Type A” pollution</td><td>Not heavy</td><td>Outdoor</td><td>Outdoor</td><td rowspan="4">Indoor solution is more attractive</td></tr>
<tr><td>Heavy</td><td rowspan="2">Outdoor with silicone rubber insulators</td><td rowspan="2">Both outdoor with silicone rubber insulators and indoor solution can be used.</td></tr>
<tr><td rowspan="2">“Type B” pollution</td><td>Not heavy</td></tr>
<tr><td>Heavy</td><td>Indoor</td><td>Indoor</td></tr>
</table>

5. CONCLUSIONS

To select between the indoor or outdoor solutions for a DC yard, there are many factors that will need to be weighted in.

- With the outdoor solution and with the DC pole voltage up to 600 kV, the operational experiences in the last two decades have been satisfactory, mainly thanks to the application of hydrophobic coatings and silicone rubber insulators.
- The uneven-wetting problem on horizontally installed wall bushings has been solved successfully through the application of hydrophobic coatings and silicone rubber insulators.
- Station post insulators of porcelain with and without hydrophobic coatings have been used for outdoor with satisfactory performance with pole voltage up to 600 kV. Station post insulators with silicone rubber sheds are available today.
- With the pole voltage of 800 kV and in polluted areas, to fulfill the mechanical requirement, it is necessary to use shorter creepage distances on silicone rubber insulators and porcelain insulator with hydrophobic coatings than that on porcelain insulators if the outdoor solution is preferred.
- For the future pole voltage of 1100 kV, increased difficulties will be encountered in realizing an outdoor solution. Indoor solution may be more attractive.
- An indoor solution will to a great extent release the difficulties for coordinating the internal and external insulation for vertically installed apparatus especially for UHVDC applications.
- Although pollutants will appear inside the DC yard building, the frequency and intensity of wetting are significantly reduced in comparison to outdoor. If the level of relative humidity is under control, wetting of pollution can be eliminated. With the short creepage distances needed, a significantly compacted design can be achieved.
- The major cost of the indoor solution is the building. This cost can partly be compensated by the reduced cost of apparatus. An improved reliability is the most important aspect in choosing the indoor solution.

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