800KVDC: EXTERNAL INSULATION, INSULATION COORDINATION, TEST LEVELS

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SUMMARY
The use of HVDC at 800 kV, has been found to be economically attractive for power blocks of 6400 MW or more for distances above 1000 km. Worldwide there is an increasing interest in the application of HVDC at 800 kV.

The smoothing reactor function is split equally between the pole and neutral, thereby lowering the reference voltage of the pole arresters and with it the pole insulation levels too.

Development work has been going on to ensure that equipment for 800 kV DC transmission voltage is achievable, and the main results are discussed.

The development, manufacturing and testing of the critical equipment needed for an 800 kV HVDC converter station is completed. The equipment has been installed in a test circuit and has been energized with 850 kV since mid November 2006.

During the R&D process essential knowledge has been gained regarding realization of converters for 800 kV HVDC, such as:

- The design rules for external insulation for converter stations including valve hall clearances.
- Mechanical design criteria for the equipment with composite insulators.
- The use of silicone rubber insulators in equipment needs careful electrical design due to the high surface resistivity and charge accumulation.
- Qualifying complicated insulation, such as bushings, comprising several different materials, requires long-term test at relevant temperature.

KEYWORDS
800 kV HVDC, Bulk power transmission, HVDC Reliability, 800 kV HVDC, HVDC, HVDC external insulation, HVDC Equipment, HVDC transmission economy, Insulation coordination, UHVD

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INTRODUCTION

Worldwide there is an increasing interest in the application of HVDC at voltage levels above what is presently used. The main reason is that most of the hydro power resources that are within convenient distance to the consumer centers have been exploited by now, and in order to meet the increasing demand for clean, renewable energy, remote hydro generation plants are built. Thus efficient means for long distance, bulk power transmission are needed: a typical scenario is 6000 MW to be transmitted 2000-3000 km.

The driving force to increase the voltage is of course the economy, but also the desire to limit the environmental impact. A comparison of the total cost for transmitting 6400 MW over 1800 km at 800 kV AC, 800 kV DC and 600 kV DC has been done. 1400 USD/kW has been applied when calculating the value of the losses. The result is that 800 kV DC is the most cost effective alternative because of higher line capacity and lower line losses. The total cost for the 800 kV alternative is 25 % lower than for 600 kV, see Fig. 1.

The environmental impact for transmission of 18000 MW is compared for different transmission alternatives, AC and DC at different voltage levels is illustrated in Fig 2. It is obvious, that 800 kV HVDC is a very attractive alternative compared with 800 kV AC due to the reduced need for transmission lines and the reduced Right-Of-Way.

To meet the needs for UHVDC transmission at ±800 kV, ABB has, with many years’ efforts, developed converter equipments for such a voltage level. In this paper results of the related R & D activities are summarize and presented.

![Fig 1. Cost comparison 600 kV HVDC and 800 kV HVDC](image1)

![Fig 2. Need for right of way, 18000 MW, comparison: HVDC and HVAC](image2)

R & D ACTIVITIES ON EXTERNAL INSULATION

General

External insulation is a key topic for the R & D of the converter equipment for 800 kV HVDC. The study on external insulation started in 1992 by ABB and STRI. During the study, existing knowledge in literature has been reviewed and a large numbers of experiments were performed. The operational experience of the existing HVDC stations from 250 to 600 kV worldwide has also been summarized. As the results, design rules for external insulation have been established for UHVDC up to ± 800 kV [1].

Operational Experience

The operational experiences from existing HVDC stations of total 80 poles (47 stations) around the world have shown that:

- A very low pollution flashover rate of 0.05 per pole per year has been achieved.
• The pollution flashover rate of these stations has no direct correlations to the voltage levels of the stations. There is no tendency and need to choose a higher value for the specific creepage distance because of higher voltage levels.
• The application of hydrophobic coatings (RTV and silicone grease) has contributed to the achievement of the low pollution flashover rate. The insulation strength, after the application of coatings, has been improved. The insulation becomes renewable.
• The silicone rubber insulators with a shorter creepage distance than that of porcelain insulators in HVDC station have operated satisfactorily. The use of silicone rubber insulators has also contributed to the achievement of the low pollution flashover rate.

Operational experience published in literatures on DC line insulators, e.g. [2-3], confirmed the fact that silicone rubber insulators can perform well with a shorter creepage distance than that of porcelain insulators. Flashovers caused by pollution are not any more the major contributing factors to the failures of the outdoor insulation.

Site Conditions
The most important factor for the design of external insulation is the actual site conditions. This is specially the case for UHVDC since the total insulation length will become a critical constrain in the design. There is no room for rough speculation and added margins. More rigorous site severity evaluation is necessary with e.g., portable test stations with DC voltage [4]. Such test station will facilitate the measurement of pollution gathered by the energized insulators. In case that only AC voltage will be used, an AC/DC correction factor has to be introduced with less accuracy as direct measurement under DC [5].

Alternatives
Various alternative solutions for external insulation have been investigated based on operational experience and laboratory tests. Some of these alternatives are valid and some still not.
• The most effective way to reduce the risk for flashovers is to reduce the number of insulators specially the one with large diameters. E.g., to have the bushings of converter transformer protruding into the valve hall, thus reduced the number of wall bushing. Also the old type of direct current transducers has been replaced with optical current transducers in modern converter stations.
• Indoor DC yard is a good alternative for heavily polluted areas and areas where pollution severity increases with time [6]. However, the add costs for the DC yard building and station operation should be taking into consideration when this alternative is selected.
• The silicone rubber insulators even with shorter creepage distance than that of porcelain insulators have been proven to be a good alternative in many stations. Today, silicone rubber housing is used for all equipments in HVDC stations. Even for station post insulators, composite types with silicone rubber sheds are available and under evaluation.
• The use of hydrophobic coatings and booster sheds on porcelain insulators have been proven, both in operation and laboratory tests, to be good alternatives for strengthen the insulation. Although, conventionally, these alternatives have been considered as only remedy methods for pollution flashovers, when come to the severely polluted conditions, they are competitive alternatives to indoor DC yard.
• Insulators with resistive glaze have superior pollution performance under AC voltage and even under DC voltage in laboratory pollution tests. However, such insulators available on market failed to pass the 1000 horse salt-fog test under DC voltage.

Laboratory Tests
Laboratory tests on porcelain insulators of station post type provided evidence on how far one can go with porcelain insulators in UHVDC stations.
• In polluted areas, for vertically installed station posts, rain tests, both even and
uneven rain, are not the dimensioning factor in comparison to the pollution tests.

- Several shed profiles that give good pollution performance in laboratory tests have been identified. The differences in performance between these profiles are marginal.
- For a SDD level equal to or higher than 0.05mg/cm², a linear relationship holds between the required creepage distance and the applied voltage for the same type of insulator in laboratory tests. This fact simplifies the dimensioning of the insulation, when the pollution level is known.
- For the shed profile with relative large shed spacing, e.g. 95/95 sheds, the test conditions like heavy rain combined with pollution is not the dimensioning factor.

Through laboratory studies and operational experience, it is clear that artificial pollution tests are not suitable to be used as type tests for full scale UHVDC equipments with silicone rubber housing. Tests that can verify the hydrophobic property and tracking resistance are more relevant tests to the performance.

The performance of booster sheds has been verified in the laboratory tests under heavy rain and pollution. Insulators with resistive glaze were tested under rain, pollution and 1000 hours salt-fog tests. Characteristics of long multiple air gaps under switching impulse voltage have also been studied to facilitate the valve hall design.

Other Investigations
Some other investigations closely related to the UHVDC applications have been made together with utilities.

- Although the results are still limited, considering the urgent need of the coming UHVDC projects, recommendations have been given for the suitable shed profiles for silicone rubber insulators of a large diameter and being installed at vertical position [7].
- Correction for high altitude is considered to be necessary when the location of the station is over 1000 meters from sea level.

CONVERTER CONFIGURATIONS

![Figure 3. Comparison of different configurations](image_url)

The configuration of the HVDC main circuit has been carefully analyzed. The large total transmitted powers make it necessary to split the system into modules. This is necessary
from the point of view of transformers, but also from the point of view of the impact of an outage will have on the host system. For example, a pole configuration, with two converter groups in series or in parallel halves the power loss upon loss of a converter group, and with adequate switchgear, ensures that a group outage will not result in a pole outage. Figure 3 illustrates the different transmission power levels that can be handled with different configurations.

An important aspect to note here is the smoothing reactance function: it is physically split between the neutral and pole sides of the converter pole; whether the configuration is series or parallel. This splitting splits the harmonics, and their value at the midpoint is almost eliminated, and at the pole side is lowered considerably. This allows the use of arresters with lower reference voltage, which in turn results in lower protective levels and lower insulation withstand requirements.

INSULATION LEVELS AND MARGINS

Deriving Withstand from Stress
The insulation levels will dictate the design of the equipments. Therefore it is critical to determine correctly the insulation levels. When considering UHVDC applications, it is important for one to aware that to push for a high LIWL, SIWL etc do not solve any problems yet create new ones. Comparison with old practice should be made with the observation of: those levels were
- picked on the back of an envelope;
- at the time when the configuration didn’t make use of symmetric smoothing inductance placing;
- arresters were less effective (ratio between protective level and operation voltage).

The resulting stresses for equipment at 800kVDC are high, and it is extremely important to let engineering criteria dictate the insulation withstand levels. There is no room for additional margins based on subjective appreciations or for increasing calculated withstand levels to “the next higher standard level”. There is no requirement on inter-changeability of equipment between different stations as is normal for ac equipment. Mechanical and thermal robustness are easy to forget, but their limits are also close by.

The main development areas have been:
- The main circuit configuration with symmetrical smoothing reactor allows the use of more stringent protective levels by lowering the steady state voltage at the middle and top of the bridges.
- Present arresters can have a tighter control of the over-voltages for a given steady state voltage.
- Careful studies have been performed with components, parameters, configuration, etc to assess the stress levels, and from them derive the necessary insulation withstand levels.

Because of the above, it is not only possible, but also advisable to use the insulation levels reported below.

At 800kVDC it is expected that the lines will be long, and can come close to fundamental frequency or second harmonic resonance. In some cases the resonance can be counteracted by the control or by the choice of smoothing reactance or dc filter capacitance. In the cases where these approaches are not enough, there may be need to use series blocking filers in the neutral. Even if that is the case, this will only affect the insulation levels of the lowermost valves and transformers, since it will be possible to use additional arresters to keep the insulation levels at the critical points at the desired levels.
At lower voltages, a simplification is often applied by forcing a ratio between the insulation withstand levels to switching and lightning surges. At the levels necessary for equipment at 800kVDC, the voltage stresses for all kinds of phenomena and transients are carefully calculated. So are the internal stresses for equipment designed to withstand them, and so are the tests that verify them. Then, depending on the materials, and the internal configuration, the ratio between withstand capabilities may or may not be close to the traditional factors. Therefore such relationship factors have no reason to exist in 800kVDC insulation coordination.

In some HVDC transmissions, the same insulation margins used for conventional equipment have been required for thyristor valves, by extension. There are a couple of important points why the same margins need not be used. One point is the extremely well known voltage grading along the valve, transiently, dynamically, and also as a function of time after application of a dc field, and even as the years pass.

This is also different from conventional equipment. Because of the above, the insulation margins for the thyristor valves need not cope with the same uncertainties as for, e.g., transformers. The margins advocated by the authors are thus:

<table>
<thead>
<tr>
<th>Insulation margins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation type</td>
</tr>
<tr>
<td>Lightning</td>
</tr>
<tr>
<td>Switching</td>
</tr>
</tbody>
</table>

*Across single valve

Study results:
From the studied transmission, the resulting stresses, or more accurately, the resulting protective levels, for the most important equipment are listed to the right.

With the results found, as given in the table at right, the margins advocated, and with the rules given in standards for other tests, test voltage levels are proposed for the main components, as shown in the table below.

<table>
<thead>
<tr>
<th>Protective levels (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
</tr>
<tr>
<td>Converter transf.</td>
</tr>
<tr>
<td>Valve side</td>
</tr>
<tr>
<td>Smoothing reactor.</td>
</tr>
<tr>
<td>Across</td>
</tr>
<tr>
<td>Smoothing reactor.</td>
</tr>
<tr>
<td>To earth</td>
</tr>
<tr>
<td>Thyristor valve.</td>
</tr>
<tr>
<td>Across</td>
</tr>
<tr>
<td>Thyristor valve.</td>
</tr>
<tr>
<td>Top to ground</td>
</tr>
<tr>
<td>DC bus</td>
</tr>
<tr>
<td>Line side</td>
</tr>
</tbody>
</table>

Test levels
For 800kVDC stations, the basic ideas for insulation coordination are the same as those applied for lower voltages; i.e. to have equipment with withstand characteristics above the expected stresses. Then, as is normal in medium or high voltage, the expected stresses are controlled by a combination of arresters and shielding. The difference for 800kVDC is that it is economically beneficial to control the expected stresses to an even higher degree, and to revise the steps leading from the expected stresses to the desirable insulation withstand; i.e. the insulation margins.

One has to remember that both aspects aim at improving the economy of a given system. Too loose control results in costly equipment, and too tight control results in costly arrester schemes and shielding. There is a human factor also: Adding margins may save some engineering costs. However, for 800kVDC, mainly due to the high non-linearity in the relationship between withstand and necessary clearances, the savings in engineering are far outweighed by the savings in equipment by a judicious choice and application of margins.

Insulation coordination studies have been performed for the dc side of an 800kV HVDC
transmission system, by ABB and different institutions. The data for the system has been assumed based on the best available estimates, with regard to preliminary design of the equipment expected for such an installation.

The different studies performed for series connected converters end up with very similar results, and the test levels used for design of the 800 kV equipment are summarized in the table below:

<table>
<thead>
<tr>
<th>Equipment</th>
<th>SI</th>
<th>LI</th>
<th>AC&lt;sub&gt;rms&lt;/sub&gt;</th>
<th>DC</th>
<th>DC Polarity reversal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer, valve side</td>
<td>1518</td>
<td>1744</td>
<td>900</td>
<td>1250</td>
<td>970</td>
</tr>
<tr>
<td>Transformer bushing</td>
<td>1518</td>
<td>1744</td>
<td>900</td>
<td>1250</td>
<td>970</td>
</tr>
<tr>
<td>Valve side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple thyristor valve, top to ground</td>
<td>1518</td>
<td>1800</td>
<td>NA</td>
<td>1040</td>
<td>(3 hs)</td>
</tr>
<tr>
<td>Wall bushing</td>
<td>1518</td>
<td>1800</td>
<td>1000 (1 minute)</td>
<td>1235</td>
<td>1030</td>
</tr>
<tr>
<td>Smoothing reactor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Across</td>
<td>NA</td>
<td>2160/n</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>To earth</td>
<td>1546</td>
<td>1950</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Pole bus at the line side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>of the smoothing reactor</td>
<td></td>
<td></td>
<td>1000 (1 minute)</td>
<td>1200</td>
<td>1000</td>
</tr>
</tbody>
</table>

EQUIPMENT DEVELOPMENT

General
In this section a summary of the R&D status, until May 2007, of the different 800 kV HVDC equipments is presented.

The equipment affected by the increased voltage level is limited to apparatus connected to the pole bus, such as converter transformers, wall bushings, thyristor valves, DC-voltage divider etc. When applicable, HVDC equipment is built up by modules where each module is provided with a proper resistive voltage grading resistor as well as an AC/transient grading capacitor. With a proper voltage grading, the voltage stress in the modules will be the same regardless the module is part of an 800 kV apparatus or a 500 kV apparatus. For oil/paper insulation systems the situation is more complicated, since it is not possible to arrange the DC grading with physical resistors: the DC grading must be secured by other measures.

For outdoor equipment exposed to pollution and rain/fog, the coordination between the internal and external voltage grading is an important issue. Bad coordination can result in damage of the insulators due to radial voltage stress.

Insulators
It has been verified by seismic studies of the different apparatus that all outdoor insulation in the DC-yard, including post insulators for air core smoothing reactors, can be done by using composite insulators.
The high surface resistivity of the silicone rubber insulators is an important factor that must be considered at the design, especially for the design of equipment with an internal voltage grading and silicone rubber external surface exposed to the outdoor environment. The surface accumulation of charges will be an important factor for the radial DC-field. With a special DC field probe, available at STRI, the surface of the insulator can automatically be scanned to measure the charge accumulation on insulator as well as the associated electrical field. See Figure 4 on the right.

**Converter transformers**

For most DC equipment real resistors take care of the DC grading. But, this is not the case for the insulation inside the converter transformers. The insulation system in the transformers is built up by a system of oil and paper, and thus the resistivity of these materials will determine the DC-grading, in the same way as the dielectric permittivity will give the transient voltage distribution.

In analogy with other equipment, the stressed volume in a converter transformer is split up in sub volumes by cellulose barriers. The electrical stress is calculated in each sub volume, and the stress in each point should be well within the acceptable criteria. Since resistivity of oil and paper vary with temperature and aging, also the voltage grading will vary. A proper voltage distribution must be ensured even for the worst possible combination of parameters.

Furthermore, the resistivity of the media is time dependent. The electric conduction in oil is done by electrons as well as by ions. When a DC field is applied across an oil gap, the ions will be drained out after some time, and thus the resistivity will change. Thus, to be able to calculate the actual stresses and time constants during polarity reversal for example, a calculation model including the ion conduction must be used. Such a calculation tool has
been developed by ABB and is used for converter transformer design.

A simplified transformer prototype has been manufactured, including all the insulation details for an 800 kV converter transformer. The transformer prototype has been tested (See Fig. 5):

- DC withstand: 1250 kV
- DC Polarity reversal: 1000 kV
- AC withstand: 900 kV
- Switching impulse test: 1700 kV

These tests were successfully passed.

**Transformer bushing**

The transformer bushings are of the same design as in the installations of recent HVDC projects. The main insulation on the valve hall side is obtained by gas, while the interface to the transformer is a capacitive core. The insulator on the air side is a hollow composite design increasing the overall mechanical strength. The general design is used for projects up to 500 kV. Since the grading of a bushing is arranged both axially and radially, and the resistivity of the materials govern the field distribution, one of the important challenges when increasing the size is to keep the internal and external field stresses balanced for a large number of operational conditions. The bushing includes several different materials, like polymers, gas, and silicone rubber that must match with oil and paper on the transformer side. The properties of all these materials have been carefully mapped at several temperatures in order to analyze the stresses at all possible conditions. The design for 800 kVdc is thus based on known materials and concepts having thorough experience from the laboratory and the field at 500 kV.

A prototype of the transformer bushing for the highest 6-pulse group has been produced, See Figures 4 and 6. The bushing has passed all type and routine tests, including:

- DC withstand: 1450 kV
- DC polarity reversal: 1130 kV
- AC withstand: 1050 kV
- Lightning impulse: 1900 kV
- Switching impulse: 1700 kV

**Wall bushings**

Just as for the transformer bushings, the wall bushing design is based on the well proven design that is used for the recent installations at 500 kV. Besides the electrical requirements, the length of the wall bushing, 18 m, figure 7, has been a mechanical challenge. The seismic withstand has been verified by calculations. The design and manufacturing of the 800 kV wall bushing is thus completed, and one wall bushing is installed in the 800 kV test circuit described further down.

All electrical and mechanical type and routine tests have been passed successfully, including:

- DC withstand: 1250 kV
- DC polarity reversal: 980 kV
AC withstand 910 kV
Lightning impulse 1900 kV
Switching impulse 1900 kV

Other pole equipment
The other pole bus components for 800 kV HVDC have also now been designed, manufactured and tested:

- Pole arrester, fig. 8
- By-pass breaker
- Pole disconnector
- DC RI capacitor
- DC voltage divider
- Composite support insulators
- DC optical current transducer
- Smoothing reactor mock up

In order to meet the requirements of a safe current contact in the disconnector, also at high wind load and at seismic events, each side of the disconnector comprises three composite support insulators in order to give a very rigid and safe structure.

DC neutral breakers
The magnitude of the 800kVDC transmission systems imposes some requirements upon their behaviour. An important one is to keep the transmitted power at a maximum during contingencies, so as not to disturb the host ac system. For the specific case of pole fault, it is important to keep the power in the healthy pole at a maximum. This in turn requires the high-speed dc switches in the neutral to be capable of switching at high current.

Aware of this requirement, ABB developed a high-speed switch concept that covers this need up to the two-hour overload limit: 5kA. Furthermore, the concept does not use a pre-charged capacitor, nor an auxiliary breaker: it employs only a resonant branch and an energy absorber in a passive arrangement. The concept employs a careful tuning of the resonant circuit to create the current zeroes that commutate it to the parallel capacitor, and then further on to the energy absorber.

The new design is very robust, since it minimises the moving elements, and eliminates the sensitive charging component. This adds to the reliability of the high-speed switches. The high-speed switch has been tested in Ludvika, at the high power laboratory, at up to 5kA.

LONG TERM TESTING

On order to verify the long term behavior of the 800 kV HVDC equipment, all relevant pieces of equipment have been installed in a long term test circuit, and have been energized at 855 kV DC since mid November 2006. They will remain energized for at least half a year. The test circuit includes a "valve hall" where the temperature is kept at 60°C, to simulate the actual operating conditions for the bushings. The transformer bushing protrudes inside the "valve hall" and is connected to the wall bushing installed in the wall. The remaining equipment is installed outdoors, together with a voltage generator and a prototype of the air-core...
smoothing reactor. The layout for the test circuit is given in Fig 12, and the actual test circuit is shown in Fig 13.

1. Transformer prototype
2. Wall bushing
3. Optical current transducer
4. Voltage divider
5. Pole arrester
6. Smoothing reactor prototype
7. RI Capacitor
8. Disconnector
9. Voltage divider, test equipment
10. By pass breaker
11. Voltage divider, test equipment
12. Transformer, test equipment

During the long term test the following parameters are being monitored:

- Surface charges on the insulators during different weather conditions
- Leakage current on the insulators during different weather conditions
- Corona on the equipment and buses during different weather conditions
- Dissolved gas in oil in the transformer prototype

After finalizing the long-term test, the equipment will be subject to repeated routine testing.

CONCLUSIONS

800 kV HVDC is economically attractive for bulk power transmission, 6000 MW, over long distances, 2000-2500 km. With the present progress of R&D converter equipment for 800 kV HVDC will be qualified within short. With proper separation and proper structure of the control and protection and auxiliary systems, the reliability and availability will be as good as, or even better than, for converters at lower voltage.
REFERENCES


